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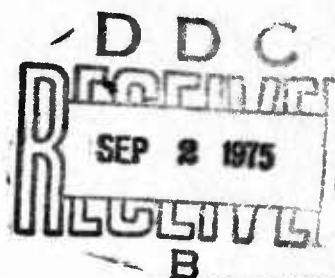
AFATL-TR-74-103

**ELECTRICAL DISCHARGE MACHINING
(EDM)
GUN BARREL BORE AND RIFLING
FEASIBILITY STUDY**

ELOX DIVISION
COLT INDUSTRIES

TECHNICAL REPORT AFATL-TR-74-103

SEPTEMBER 1974



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AIR FORCE ARMAMENT LABORATORY

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Electrical Discharge Machining

(EDM)

Gun Barrel Bore And Rifling

Feasibility Study

Robert M. Greene

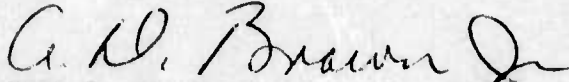
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FOREWORD

This report was prepared by the Elox Division, Colt Industries, Davidson, North Carolina, 28036, under Contract No. F08635-73-C-0072 with the Air Force Armament Laboratory, Armament Development and Test Center, Eglin Air Force Base, Florida. Captain Larry R. Lawrence (DLDG) managed the program for the Armament Laboratory. This report covers work performed from January 1973 through December 1974.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



ALFRED D. BROWN, JR, Colonel, USAF
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ABSTRACT

A 12-month program was conducted to advance the technology of the Electrical Discharge Machining (EDM) process to be applicable to the stringent requirements of gun barrel boring and rifling. The type of barrels employed in the test were .220 swift gun barrel liners and gun barrel blanks. The various materials were selected on the basis of their resistance to withstand the high stress, high temperature, high pressure, high rate of loading, and high erosion rates encountered in high performance gun designs such as the GAU-7/A and the GAU-8/A. The materials investigated were iron/nickel base superalloys, cobalt base superalloys, tantalum, columbium, and tungsten refractory alloys. These materials do not lend themselves to traditional types of machining, and an investigation was undertaken to see if advances in the state of the machining art, such as EDM, were capable of the task. The final effort on the program consisted of boring and rifling 18 gun barrel blanks for delivery to Philco-Ford Corporation, Aeronutronic Division, Newport Beach, California, for final fabrication and testing in .220 swift M-60 test barrels. These barrel blanks, however, were out of specification and could not be fabricated into test barrels.

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GLOSSARY OF TERMS

The following definitions are related to their common usage in the EDM industry and are intended for interpretation within the confines of the subject test only.

Power Supply: The power supply is the electronic unit which generates and controls the electrical discharges.

Machine Tool: The machine tool is the mechanical unit which holds the work piece and guides the electrode.

Electrode: The electrode corresponds to the cutting tool in conventional machining and is analogous to a drill. The exact configuration of the electrode will be reproduced in the gun barrel.

Amperes: Amperes are the measurement of cutting current employed in the EDM process and are an indication of metal removal rate.

Over Cut: Over cut is the differential in size between the electrode and the work piece (gun barrel). The over cut on the .220 swift barrels was 0.001. (See Figure 8.)

Spark Length: The spark length is the distance between the electrode and work piece (gun barrel) which the spark travels in machining. The spark length is equal to the over cut.

Spark Gap: The spark gap is synonymous with the spark length and spark over cut.

Dielectric: The dielectric is the nonconductive oil used in the EDM process which serves to cool the barrel and carry away the machined chips.

SECTION I

INTRODUCTION

During recent years, the necessity for improved gun barrel designs has become increasingly apparent with the inception of new high performance weapons systems. The requirements for high muzzle velocities, higher firing rates, and extended burst firing schedules have isolated barrels as perhaps the most critical of performance-limiting gun components. With the evolution of the insulated composite gun barrel as an outgrowth of the Air Force funded Contract No. F08635-69-C-0156, entitled "Equilibrium Temperature Gun Concepts," came the capability of providing more severe firing schedules without structural failure. In 1970, Air Force Contract No. F08635-70-C-0116, entitled "Composite Barrel Materials Research and Development," had as its objective the advancement of gun barrel technology by developing an insulated barrel blank that was erosion resistant in the rapid firing environment.

A materials selection program was conducted and resulted in the use of superalloys having iron/nickel, tantalum, cobalt, or columbium as a main constituent or base material. A recommendation of the materials research and development contract was to develop methods for the machining and rifling of the superalloy and refractory metal liners. An Electrical Discharge Machining (EDM) boring and rifling feasibility study, Contract No. F08635-73-C-0054, was issued which is the subject of this report. This contract consisted of a three-phase effort to develop the EDM equipment, EDM bore and rifle gun barrel blanks of various superalloys, and EDM size various coated and solid barrel blanks. A total of 18 gun barrel blanks were EDM bored and rifled and delivered to Philco-Ford Corporation for inspection, final assembly, and testing. The barrels were to be fabricated in the .220 swift size with the intent that the performance tests would have been directly applicable to larger caliber, high cyclic, high performance guns.

The technical approach is presented in Section II. Sections III and IV present detailed descriptions of the process, the equipment used, and the results of the research and development effort. Section V contains the resulting conclusions.

SECTION II

TECHNICAL APPROACH

The objective of this program was to advance gun barrel technology by developing a machining method for high temperature erosion resistant alloy gun barrel liners. Superalloy or refractory metal liners offer a potential improvement in erosion life and also increase performance capabilities to withstand higher firing rates, longer bursts, and higher propellant flame temperatures. The superalloys present a difficult machining problem by conventional methods such as gun drilling. The EDM process was investigated due to the fact that material hardness and toughness does not present a difficult problem.

The approach to the problem was (1) to develop a machining center capable of electrical discharge machining bores having a length-to-diameter ratio in excess of 100:1 to develop an electrode and electrode holder that would produce reliable and economical barrels and (2) to develop a rifling technique. Gun barrel materials falling into the superalloy classification were fabricated into the .220 swift barrels and forwarded to Philco-Ford Corporation, Aeronutronic Division, for installation into insulated composite gun barrels. The barrels would then be evaluated by the Air Force. A two-phase, 12-month program was conducted.

Phase I consisted of the design and fabrication of an EDM system capable of producing the .220 swift bore and rifling geometry. Preliminary test cutting was performed to evaluate electrode materials, wear rates, and geometry. The general arrangement of the system is shown in Figure 1.

Phase II involved test cutting and analysis of a total of 18 gun barrels of various superalloys. The gun barrels were finish bored and rifled by the EDM process from barrels having an initial hole of .210 diameter. A total of six barrels were completely bored from blanks by the EDM process: these consisted of two CG 27 and four VM 103 barrels. Some barrels that could not be produced by the EDM process in the present state of the art were the TA-10W and the CVD tungsten coated barrels. Further explanation is given in Section IV relating to the EDM process limitations. Of the gun barrels produced by the EDM process, the barrels that showed the most promise from a producibility point of view were the CG 27, L-605, and the INCO 718. The barrels produced were approximately 22 inches long and were fabricated complete prior to encapsulation in the insulated barrel liner. Further Phase II details are presented in Section IV. The gun barrels are shown in Figures 9 and 10.

SECTION III

PHASE I: DEVELOP MACHINING SYSTEM AND TECHNIQUES

The goal of Phase I was to develop a machining center that would be capable of producing small bores for the .220 swift barrel 22 inches long. The machining center consisted of a machine tool, the Elox Modified TC 50 Power Supply, and an electrode guide system. The machining center is shown in Figure 1.

3.1 THE ELOX MACHINE TOOL

The machine tool was a modified vertical electrical discharge machine tool having 24-inch stroke. A removable front door was provided for ease of loading and unloading the work station with the work pan door removed.

The ram is attached to a hydraulic cylinder which is controlled electrically by a servo valve. The servo system receives electrical signals from the arc gap. Small changes in voltage cause the servo valve to distribute hydraulic fluid to the required side of the cylinder. The electrode is then advanced or retracted at the arc gap. (See Figures 3 and 11.)

The work station is enclosed to contain the dielectric coolant. The coolant is brought into the working area by pressurizing the machine base with air forcing the fluid into the work tank. (See Figure 4.)

The electrode is rotated in its holder to provide even electrode wear, create round holes, better electrode alignment, and ability to offset a coolant hole so that no projection would be left in the cavity. The electrode alignment was critical with respect to holding the finished bore size as well as the bore geometry. Electrode axial misalignment would have the effect of producing an oversize hole when rotated and an oblong hole when not rotated. The electrodes were ground to size while assembled on the electrode carrier in an attempt to assure alignment. Concentricity of the electrode and electrode guide was maintained by chucking on the rear electrode guide while supporting the front electrode guide on a live center during the grinding operation. (See Figure 7.) Electrode arrangement is shown in Figures 4, 5, and 6.

The gun barrel blank was clamped in the vertical position between two V-block locators. The electrode carrier is guided in a bushing whose centerline coincides with the work piece. The machine tool has provisions for rotating the electrode at a variable rate by means of a silicon controlled rectifier drive. The rate of rotation ranged from

10 to 300 RPM and was only critical in that the electrode guide system would begin to wobble at the higher rates. The reason for the electrode wobble at the higher speeds is associated with the critical shaft speed and elastic instability of the electrode carrier. An electrode wobble would have the effect of producing a barrel that would have a bulge at the approximate midpoint of the barrel. The change of bore size at the midpoint of the barrel relates to a harmonic curve and is most severe at the degree of least stiffness. The bulge in the barrels was not discovered until rubber replicas of the bore were reproduced. This was believed to be due to the high slenderness ratio associated with the .220 swift barrels. Most of the EDM cutting was done at the lower rates of 30 to 100 RPM. Further provisions are made to generate the 10-inch, right-hand spiral by means of a cam coupled to the vertical motion of the ram travel. The electrode enters the barrel from the breech end and bores the hole by means of the EDM process. (Basic theory of the EDM process is explained in paragraph 3.1.) As the EDM electrode advances into the barrel, the electrode alignment is provided by means of an insulated pilot immediately following the electrode. Figures 5, 6, and 7 show the EDM electrode and electrode carrier.

3.1.1 THEORY OF EDM

A review of the fundamental principles of EDM will help in understanding the machining process employed. The simplified schematic shown in Figure 11 will provide a basic description of the thermo-mechanics involved in the EDM process.

EDM is a precision metal removal process utilizing an accurately controlled electrical discharge to erode metal. These discharges are generated from 1 to 250 kilohertz per second.

To visualize the EDM process, picture one electric spark being generated and passing from a negative (-) charged electrode to a positive (+) charged work piece. The spark applies energy which brings the metal to a molten state, and the small amount of metal which is removed in the presence of dielectric oil is immediately resolidified into a small hollow sphere.

The interaction between the electricity, electrode, work piece, and dielectric oil removes the metal, leaving a small eroded pocket in the work piece.

The EDM process machines any electrically conductive metal regardless of its hardness.

3.1.2 METAL REMOVAL RATE

Figure 12 shows the current progressively increased from 1 ampere to 4 amperes. As energy per spark is increased by a factor of four, the metal removal is increased by the same factor. In each succeeding case, a larger volume of work piece material was removed. As machining current is increased for a particular discharge frequency, metal removal rate increases.

The power supplies are rated by ampere output. The ampere output is indicated by the number following the "T" prefix. Maximum outputs for the power supplies are 50, 100, and 200 amperes.

It will be noted that doubling the output current doubles the metal removed per spark. In this way, the ampere output is supplied that best suits the work piece needs. By calculation then, it can be determined that "T" power supplies remove 0.00083 cubic inch per minute per ampere when machining steel with a graphite electrode. This figure is under ideal circumstances for a reverse polarity cut and would give minimum tool wear.

If conditions are excellent, a standard polarity cut in the midrange frequency may go as high as 0.0014 cubic inch per minute per ampere, however the tool wear would be a maximum.

Two basic controls on the power supply are used in conjunction to apply energy to the cut. They are illustrated schematically in Figure 13 (a).

The current control increases or decreases the length of time the current is allowed to flow per pulse. (This is called on-time.) The current limit sets the amount of current that will be allowed to flow during on-time. (Current limit is also called peak current.)

The shaded portions in Figure 13 (a) represent the pulse energy which is a combination of the two controls. The advantage of variable on-time and current limit is speed of metal removal and reduced electrode wear. The illustrations are equal in energy but are different in mode of cut.

"A" has faster metal removal rate than "C" but will have some electrode wear. "C" will have little or no wear but will take longer to do the same job.

There is no definite formula for the amount of current that a particular size electrode will sustain. It would not be logical when milling with a small end mill conventionally to take a heavy cut with this cutting tool. In order to take heavy cuts, the size of the cutting

tool would have to be increased. Too much energy in too small an area will result in the breakdown of that cutting tool (electrode). Attempting to use high current levels through thin or sharply defined detail will cause unstable cutting and possible damage to the electrode or work piece. Therefore, the size of the EDM cutting tool must be increased.

As a basic rule of thumb, to obtain good removal rate efficiency, one square inch of graphite electrode per 50 amperes of cutting current should be used. It can be proven that the area for the .220 swift electrode limited the amperage to 2 amperes.

As in conventional cutting tools, the addition of elements such as nickel, chrome, molybdenum, and other alloys sometimes slows down the cutting rates of EDM when compared to the cutting of low carbon steels. Many times, however, the correct choice of electrode material offsets this condition. An example would be the EDM cutting of tungsten carbide material with copper tungsten electrodes. This combination produces a very stable cut. However, current levels should not exceed 15 amperes when cutting carbide or cracking and possible breakage could occur.

Increasing metal removal rate or amperes effects one other condition: surface finish. As the amperes increase, the spark cavity size in the work piece also increases, or increasing the amperes increases the roughness of the surface finish. Since volumes are dealt with in EDM metal removal, it is important to remember that surface finish roughness does not increase proportionally with machining current. In other words, doubling the amperes does not cause the surface finish to be twice as rough.

3.1.3 DIELECTRIC COOLANT

The most important single factor in the successful operation of the EDM process is the removal from the working gap of the chips of particles. Flushing these particles out of the gap is the key to good operating conditions. As in more conventional machining methods, if cutting particles are allowed to lay in the cutting tool area, sooner or later machining conditions will degenerate. The ideal flushing situation for EDM is coolant under pressure at the working gap. Poor flushing will increase the cutting time and costs.

There are three functions required of the dielectric:

1. It must insulate until the required conditions are achieved between electrode and work piece.
2. It must cool the work, electrode, and particles.
3. It must flush the particles out of the arc gap.

The dielectric used is an oil with a trade name of Eloxol 13®. Eloxol 13® is a low viscosity oil with a dielectric strength of 170 volts per mil (0.001). Other media include silicone oil, deionized water, and certain gases. Some of these offer advantages in removal rates for production applications or ease of cleaning and lack of contaminants.

The method of flushing the coolant and the eroded particles from the gun barrel is shown in Figure 18. The electrode has coolant holes which are located off the centerline of rotation to provide maximum coolant efficiency. In cases where rotation of the electrode was not used, a small spike would protrude up into the coolant hole and would eventually break off causing erratic EDM cutting. The size, location, and coolant pressure were critical parameters in the machining of the gun barrels. An average coolant pressure of 10 PSI at the coolant manifold was used to EDM the gun barrels.

3.1.4 SURFACE FINISH

As with any machining operation, surface finish of the machined area is a prime consideration. Fast cutting was accompanied by a rough surface finish. Finer machining calls for slow machining. For EDM, this finish control is called frequency and is built into each power supply. This control has 10 positions. (See Figure 14.)

The frequency being controlled is the number of sparks per second between the electrode and work piece. The selection of spark frequencies is as follows:

<u>Frequency Control</u> <u>Position</u>	<u>Sparks per Second</u> <u>Frequency</u>
1	500
2	1,000
3	2,000
4	4,000
5	8,000
6	16,000
7	32,000
8	64,000
9	130,000
10	250,000

To understand how frequency control affects surface finish, certain conditions must be considered. For example, holding the amperes at some constant value and varying the number of sparks per second. One spark per second at 5 amperes contains a certain amount of energy and will remove a given volume of material. [See Figure 15(a).] Figure 15(b) has two sparks per second with the same 5 amperes of energy divided between the two sparks. Consequently, the volume of work piece material removed for two sparks is still the same as one spark per second at 5 amperes. The frequency or number of sparks is divided into two sparks instead of one spark, and the resulting finish will be improved.

Figures 15(c) and 15(d) show the 5-ampere cutting current, but the frequency of the spark has been increased to 4 and 8 discharges per second, respectively. In each case, the volume of material is still equivalent to one spark per second at 5 amperes. Surface finish improves as the spark frequency increases due to the reduction of energy per spark.

It is also possible to change surface finish by holding spark frequency constant and varying the amperes. With this process, it is possible to vary both spark frequency and cutting amperes. Figure 16 explains the reasons and advantages of this control.

A 5-ampere discharge [Example 16(a)] will remove a given volume of work piece material. This makes a cavity of a given size and determines surface finish. If current were increased to 10 amperes [Example 16(b)] and the frequency were doubled, there would be two discharges of 5 amperes each. Metal removed per 5-ampere discharge is the same as Example (a) so that the resulting surface finish of Examples (a) and (b) are identical. Since machining time is dependent upon gap current, it would take one-half as long to remove the given amount of material at 10 amperes as at 5 amperes. Surface finish would remain the same for each operation, but the 10-ampere rate would machine twice as fast as the 5-ampere rate.

Understanding the effects of spark frequency and amperes is very important. By proper use of the spark frequency and ampere control, it is possible to predetermine the settings for most efficient use of the Discharge Power Supply.

It is not possible, due to electrical considerations, to obtain the higher current levels at high frequency; consequently, finishing cuts are performed at a lower percentage of the total current. This condition is a direct parallel to conventional machine practice such as lathes, mills, grinders, etc., in that rough cutting expends high energy while a finish cut calls for a much lighter touch.

The surface finish obtained on the gun barrels varied between 80 and 120 Root Mean Square (RMS) as measured on the EDM surface finish gradient scale supplied by Electro Tools Incorporated. Finer finishes are obtainable through improved rotating electrode guide systems and reduced cutting rates. The rigidity of the .220 swift electrode holder was not sufficient to improve surface finishes below 80 RMS.

3.2 POWER SUPPLY

A 50-ampere power supply was used for all test cuts along with a laboratory oscilloscope to monitor cutting efficiency. A brief description of the individual functions of the power supply controls [Figure 13(b)] is given in subsection 3.2.1. Some parameters of the EDM machining characteristics were also described under subsection 3.1.4, Surface Finish.

3.2.1 POWER SUPPLY CONTROLS

A brief description of the power supply controls will aid in visualizing the operating parameters used in machining the gun barrels. (See subsection 3.2.2 for gun barrel machining parameters and Table 1.)

Voltmeter: The voltmeter indicates the average voltage at the arc gap. The voltmeter contains red and green lamps to indicate the scale in use. The green light glowing is for the low scale, and the red light glowing is for the high scale. The voltmeter is an aid to the operator as a visual check of cutting conditions at the arc gap.

Voltage Knob: This knob helps stabilize cutting conditions by changing the space between the cutting face of the electrode and the work. Although this change is not measurable, it is often advantageous in that it allows better chip removal by the coolant flow and thereby improves feed stability.

Ampmeter: The ampmeter shows the value of pulsating D. C. cutting current passing through the arc gap. The ampmeter has a red light which glows when the high scale is used and a green light which glows when the low scale is in use. The lamps are selected automatically by the frequency and current limit control settings.

Current Knob: This knob sets the on-time of the work pulse. Moving the knob clockwise increases the on-time and thereby increases cutting current.

Current Limit Switch: This switch is used in conjunction with the current knob to set the amount of current that will flow during the on-time. Increasing the setting of the current limit will increase cutting current.

Electrode Feed: The electrode feed adjusts the down-feed of the ram during automatic operation and operates when cycle start button has been pushed and hand-auto switch is in AUTO.

Frequency: A 10-position switch is provided to select the desired number of sparks per second.

Output Switch - Voltage Level: Standard position sets 70 volts at the arc. This setting is used for the majority of cuts. HI POL doubles the voltage. ELO-POLISH is fine cutting and is used with high voltage.

Metal Graphite Switch: This switch is set according to the type of electrode being used.

3.2.2 POWER SUPPLY PARAMETERS FOR MACHINING BARRELS

The frequency setting for the gun barrels was generally between position number 6 and 7, 16 and 32 kilohertz, respectively. (Reference Table 1.) While better surface finish could be expected at a higher frequency setting, the cutting efficiency became erratic. This was attributed to the decrease in over cut between the electrode and the work piece. Electrode wear rates are also increased at the high frequencies. A compromise frequency was employed to prevent having to change electrodes in the middle of the cutting operation. This was necessitated by the machine stroke limitations.

3.3 EDM ELECTRODE DEVELOPMENT

A series of test cuts were made to determine the electrode material and EDM cutting parameters. The results of the tests are tabulated in Table 1. The evaluation of the test cuts showed graphite electrode material to be superior to other conventional electrode materials, such as copper, silver-tungsten, and copper graphite. The melting temperature of graphite is 5430°F. By comparing the melting temperatures of the gun barrel materials with graphite, a qualitative prediction can be made concerning EDM efficiency.

The greater the differential between the melting point of the electrode material and the work piece, the better the EDM removal rate provided the melting point of the electrode is the higher of the two materials. For example, gun barrels of materials CG 27 or L-605 have the lowest melting temperature relative to graphite and are the easiest to machine by means of the EDM process. This rule is a general one and does not always apply. In the case of free silica materials or free graphite particles, the above rule does not apply. A qualitative estimation of EDM efficiency can be made on the basis of melting points. (See Figure 17.)

The electrode materials used to EDM the gun barrels were EDM-3, EDM C-1, and EDM C-3. These particular materials are isotropic graphite and were chosen because of their ability to be manufactured in the fragile thicknesses and geometry required for the rifling electrodes.

EDM-3 is a pure graphite material having high strength and small grain size. EDM C-1 and EDM C-3 are equally acceptable graphite materials but with a small amount of copper impregnated into the graphite to improve ductility and cutting speeds.

Silver tungsten and copper electrode materials were also tried as an electrode material but these exhibited poor wear rates and were subsequently discarded as a candidate.

SECTION 1V

PHASE 11: EDM OF CANDIDATE BARREL BLANKS AND ANALYSIS

4.1 TESTING PROCEDURES

The barrel blanks were finish bored and rifled at the contractor facility. Some barrel blanks were bored complete while others were previously bored undersize by the conventional process of gun drilling. The object of the program was to finish bore and rifle a total of 18 barrels and deliver to Philco-Ford Corporation, Aeronutronic Division, for assembly into insulated gun barrels. The barrel blanks are shown in Figures 9 and 10 where the rifling geometry and bore size are defined.

The gun barrel blanks were installed vertically in the machine work station and the electrode entered the barrel from the breech end. In the EDM process there is no physical contact between the work piece and the electrode. (See Figure 18.)

Boring the initial hole in the gun barrel blanks by the EDM process was possible in the CG 27, L-605, and INCO 718 materials but was not competitive with gun drilling. The small bore diameter was a detriment to efficient EDM cutting due to the fact that the amount of amperage available to the cut is proportional to the electrode end area. The area of the roughing electrode was 0.0322 square inch. The maximum amount of current that could be employed in the EDM cut was 3 amperes. The time required to rough bore a single barrel blank ranged from 9.7 hours to 15.6 hours. The rate of penetration of the EDM bore into the blind hole of the barrel blank was nonlinear. The first 6 to 8 inches of cut would progress at the predicted rate of 15 inches per minute but would progressively deteriorate from this depth and deeper. On the VM 103 and TA-10W materials, the tendency was to DC-arc at this point which was an indication of poor coolant flushing conditions at the electrode gap. At the depth of 6 to 8 inches, the coolant pressure was not sufficient to force the EDM particles out of the small gap between the electrode and the work piece. The particles would then cause a short circuit and the machine ram would go into oscillation; further cutting beyond the point of the short circuit was not possible until the offending particles would become dislodged and forced from the EDM gap.

It was observed that barrels having an initial bore had a natural assist from gravity affects on the EDM particles and coolant flow through the gap was more controlled. For this reason, the barrels were gun drilled to provide an initial hole through the barrels.

From the summary of the EDM cutting times (see Table 3), it can be determined that some barrel materials cannot be machined by the EDM process in the present state of the art. It is believed that the lack of success in machining these materials is due to the high melting temperature-high conductivity properties of the gun barrel materials.

The materials that were least responsive to the EDM process were the VM 103, TA-10W, and the CVD tungsten coated. Test cuts were terminated when it was apparent that the electrode wear rates were so high as to be impractical. The fact that the barrels were not usable does not necessarily mean in all cases that the EDM process was not capable of producing good parts, nor is this an adequate indication of machinability rating. The biggest hindrance to producing an acceptable barrel was not the machinability, but rather the small bore. The small bore limited the electrode guide shaft diameter to less than 0.187 diameter in order to provide clearances. Any flexing of the shaft would cause the steel shaft to touch the side of the barrel bore with resultant secondary EDM cutting. A thin layer of insulation was applied to the shaft to control the EDM cutting, but attempts to provide a guide support thwarted the coolant flow.

Having a small bore or undersize hole existing in the barrel previous to the EDM operation greatly reduces the time required to perform the finish bore and rifling operation.

A dielectric coolant is pumped under pressure through the center of the electrode which flushes away the machined chips or particles and cools the work piece. Another function of the dielectric is to act as an insulator between the electrode and the work piece prior to the application of the electrical pulse. This insulation property permits the charge and thus the voltage to build up. The breakdown voltage is a function of the dielectric and the electrode-to-work piece gap spacing. When sufficient voltage is applied, breakdown of the fluid occurs and current is conducted from the electrode to the work piece. During peak current periods the EDM fluid removes heat from the electrical discharge arc column and is deionized. When the current is stopped by shutting off the power supply, rapid quenching of the work piece occurs. The minute molten particles that have been removed from the work piece are also quenched and are flushed away by the recirculation of the coolant.

The electrode-work piece arrangement is shown in Figure 18. A general synopsis of the EDM process is contained in subsection 4.2 that further explains the process characteristics. The electrode is under hydraulic-servo control and as the end gap relationship between the work piece and electrode increases, the electrode advances into the cut. When the electrode has advanced entirely through the work piece, the cutting cycle is complete.

Metal removal rate is a function of the work piece melting point and conductivity among other variables. Generally speaking, the greater the differential between the melting point of the electrode and the work piece the higher the EDM efficiency.

Materials with low melting temperatures erode rapidly while the gun barrels, with their attendant high melting points, erode slowly. The efficiency of the EDM process was poor because the melting temperature of the gun barrels approached that of the electrode material.

Graphite material has a high melting temperature and therefore makes a good electrode material. From Table 2 it can be seen that tungsten (chemical element W) has a higher melting temperature than copper (chemical element Cu) and would eliminate copper as a practical choice for an electrode when machining tungsten coated barrels. The metal removal rate is measured in terms of cubic inches of material removed per minute per ampere times 10^{-4} . Again, it is readily seen that for a graphite electrode (tool material) having a melting temperature of 4000°C and a gun barrel (work piece) having the same melting point, 0.000005 cubic inch would be removed from the electrode while 0.0001 cubic inch is being removed from the work piece. Stated simply for the above example, the electrode wear rate would be 20 to 1 in favor of the electrode, or one inch of usable electrode length would be required to bore a hole 20 inches deep in the gun barrel. In practice, the electrode required to EDM bore the gun barrels averaged 4 inches, and in the case of the CVD tungsten coated barrels, required 4 inches to penetrate a depth of 2.5 inches. No explanation of this phenomenon is given at this time for the unusual wear rates.

4.1.1 GENERAL EDM PROCESS CHARACTERISTICS REVIEW

The work piece metallurgy in EDM is structurally similar to the heat affected zone in a fusion weld. According to the previously explained theories, material is removed from the work piece by a thermal mechanical process. The work piece surface reaches the melting point of the metal and the metal just below the surface is likewise heated but to lower temperatures. The region in which the heating is sufficient to cause a change in the metallurgical structure is called the heat affected zone.

HEAT AFFECTED ZONE

The heat affected zone of an EDM work piece consists of two parts. The layer starting at the surface which was heated to the melting point will show the characteristics of severe quenching because as soon as the arc was extinguished, the coolant rushed back across the surface quenching it. A quenched outer surface may be extremely hard, in fact as hard as that produced by any quenching heat treatment the parent metal would normally permit. For steels, the surface may be around Rockwell C70 if the carbon and alloy contents of the surface layer are high enough. The second layer will show the result of heating and cooling without the extreme temperatures of melting. Thus, EDM may tend to soften that material slightly due to recrystallization and grain growth.

The thickness of the heat affected zone is dependent upon how the material was EDM machined. Roughing at high currents with big sparks leaves a rough surface and a correspondingly deep heat affected zone. Fine finishing at low current, high frequency, and very small sparks leaves a very thin heat affected zone. The thickness may vary from 0.010 inch for roughing down to 0.0001 inch for fine cutting, and in some cases, it may be almost impossible to determine how thick the zone is because it

may not appear in photomicrographs. The heat affected zone for the CVD tungsten coated material shown in Figure 19 is 0.001 inch thick. The thickness of the heat affected zone did not vary significantly on the Air Force materials.

WORK PIECE SURFACE CONDITIONS

If the physical principles of the EDM cutting process are understood, then the concepts of over cut, surface finish, and taper can be readily grasped. During the EDM cutting process, the spark creates a molten particle which is expelled from the work piece surface into the gap between the work piece and the tool where it is cooled in the dielectric fluid. The work piece does not touch the cutting tool directly. Several corollaries emerge from this relatively simple picture of the EDM process.

OVER CUT

Since the cutting tool (electrode) does not touch the work piece, it follows that there is a space or a gap between the tool and work piece which may be called over cut. The perpendicular distance from the work piece to the tool at the end of a cutting operation defines the over cut. This distance is roughly equivalent to the gap spacing at any time during the cut as well as being the final gap between the tool and the work piece. The over cut then should depend upon the open circuit voltage of the power supply because the higher the initiating voltage is, the wider the gap will be. Moreover, the gap will be larger during a roughing operation than it will be during a finishing operation because the current pulse during a roughing operation expends a large amount of energy in each pulse. This tends to create a larger crater in the work piece and statistically the overall gap will be larger after a series of large pulses than it will be after a series of very fine finishing pulses.

The surface finish that results from the EDM process is also a function of EDM physical principles. Since material is always removed in small droplets, one would expect the work piece surface to be made up of a large number of very small overlapping spherical cavities. Moreover, the size of the cavities should be related to the sizes of the sparks that form them, which, of course, are directly related to the amount of energy within the pulse that caused the cutting operation. Going back one step further, the size of the pulse is then related to either the size of the capacitor in an RC power supply or to the magnitude of the current pulse generated by the power supply. The gun barrel blanks ranged in surface finish from 80 to 100 RMS with a heat affected zone of 0.008 to 0.001 for all candidate materials. The surface finish could have been improved by one of two methods: utilizing a copper tungsten electrode, or cutting at a higher frequency. Copper graphite was disqualified as a candidate electrode because of the relatively poor wear rates and the difficulty of producing the rifling geometry. Cutting on

a higher frequency was not practical on the .220 swift barrels due to the extremely small over cuts associated with the higher frequency. The over cut on a tap 10 cut (250,000 cycles per second) is 0.0007 inch wide and would require a very accurate, rigid electrode guide system. It is not possible to build a guide system of sufficient stiffness in the .220 swift barrels. Larger caliber barrels having a diameter of 0.380 inch or greater could be produced having a 32 to 40 RMS surface finish provided the length-to-diameter ratio did not exceed 50:1.

Compared to a surface that has been machined by conventional cutting operations, the EDM work piece surface always appears to be less glossy and to have more of a satin or matte finish for the same RMS finish. Again, this is easily understood in terms of the spark process as opposed to the conventional machining process. The EDM cut occurs as a large number of individual particles are removed; whereas, the conventional machining process tends to smooth, scrape, or polish the surface during the cutting process.

4.1.2 EDM METALLOGRAPHY

EDM is a thermo-mechanical process that produces a typical recast layer and heat affected zone on the material surface. EDM applied to the superalloy is no exception. Photomicrographs of the CVD tungsten coated with WC 3015 material are shown in Figure 19, along with Figure 20 which outlines a characteristic EDM surface. The photomicrograph shows gray surface patches of oxides or other compounds resulting from an interaction of the molten tungsten and the oil in which the work piece is submerged during the EDM process. Immediately beneath these gray patches are traces of a thin layer of quenched metal. A light etching band of grossly overheated (aged) metal, but apparently not recast, lies beneath the surface, followed by material which has a normal appearance for this alloy. While it is not possible to measure the hardness of the recast layer because of its thin dimension, there is a characteristic loss of hardness on the quenched layer. At 0.001 inch below the surface, the hardness was only two points lower than the parent metal on the Rockwell "C" scale. It may be concluded that the microstructural effects produced by the EDM process, in this case, were confined to less than the first 0.001 inch of material beneath the surface.

In previous EDM surface studies, it has been determined that the significant surface integrity characteristics of most materials, namely residual stress profiles and fatigue behavior, are relatively independent of processing parameters. While current density can be varied widely (resulting in marked differences in amounts of recast layers, etc., formed on the surface), the resulting residual stress and fatigue behavior which govern materials performance are relatively constant. For EDM it is generally assumed that there is a single or at least a narrow band of mechanical properties behavior for a particular material. Examples of typical EDM surface characteristics and residual stress diagrams are included in Figures 19 through 21 for comparison.

4.2 TEST RESULTS

The objective of the program was to determine the feasibility of machining gun barrel inserts by the EDM process.

From the information supplied in Tables 3 and 4, it is clear that some materials cannot be machined by the EDM process in its present state of the art. This is due primarily to the high melting point of the materials, high ratios of length versus diameter of the bore, and inability of electrode manufacturers to produce electrodes that are efficient conductors with melting temperatures in excess of 7500°F.

A total of 21 barrel blanks were delivered under contract to Philco-Ford Corporation for installation into composite insulated gun barrels for further test and analysis. None of these barrels were within the specified tolerance; therefore, no further testing is to be done.

A qualitative comparison of machinability is given in Table 4. The materials which were not machinable by EDM were the CVD tungsten coated, TA-10W, and the VM 103. Of these three, the VM 103 was marginal in that while the cutting rate was so slow as to be considered impractical, three barrels were produced. The quality of the barrels was inferior to the more readily machinable materials. A comparison of melting temperatures of the candidate barrels with existing electrode materials explains the reason for the poor machinability.

The dimensional quality of the gun barrels produced by the EDM process proved to be nonuniform in that the bore diameters were not consistent throughout the length of the barrel. Rubber replicas of the bore and rifling geometry were produced by Philco-Ford Corporation and forwarded to the Air Force Armament Laboratory. The rubber replicas of the barrel bore showed some barrels to be as much as 0.020 oversize on the bore diameter. The bore size would be generally to size at ends but would be oversize at the approximate midpoint of the barrel. It is believed that the bow was caused by the lack of rigidity of the electrode guide system. The electrode guide shaft would become unstable at certain critical speeds causing a harmonic deflection directly attributable to the length-to-diameter ratio of the shaft.

SECTION V

CONCLUSIONS

The fabrication of the small bore barrel blanks resulted in the following conclusions:

1. EDM has proven to be only a partially successful process for producing barrels composed of the superalloyed materials. The extremely deep holes required in gun barrels can be produced provided the barrel bores are of sufficient diameter to permit a rigid electrode guide system. Small bore barrels having a length-to-diameter ratio in excess of 50:1 pose a considerable electrode guiding problem for the EDM process. Electrode carriers become elastically unstable with the result that the carriers would flex and cause secondary cutting at approximately the midpoint of the barrel. Attempts to stiffen the carriers or to provide insulation for them were hampered by the small bore. Electrode guide problems are considerably improved if the bore exists in the gun barrel prior to the EDM operation.
2. Electrode life was predicted on test cutting of heat resistant alloys but did not hold true for the candidate barrel materials. This resulted, in some cases, in having to change rifling electrodes in the middle of the EDM cut and rifling alignment suffered. More research is needed to select better electrode materials. A direct relationship exists between the differential of the melting temperature and conductivity of the electrode-work piece combination relative to metal removal rates. Generally speaking, materials having high melting temperatures and low conductance values make the best electrodes. Since the superalloys themselves have high melting temperatures, selection of a suitable electrode material becomes critical.
3. More research is needed in the machine tool, electrode-guide system, and electrode rotational speed. The vibratory dynamics of various electrode size-speed combinations should be investigated to eliminate the oversize bore condition that exists at the midpoint of the barrels.
4. The EDM barrels exhibit metallurgical characteristics which should prove beneficial to reducing the metal erosion rates. This is due to the unique omnidirectional mat-surface finish and the slight hardness increase of the recast layer associated with the EDM process. Frictional forces are also reduced due to the ability of the cavities to absorb some of the impurities, permitting the projectile to ride on the raised ridges.
5. The accuracy requirements of the gun barrels are within the scope of existing EDM technology; however, the small bore rifles pose a formidable mechanical problem.

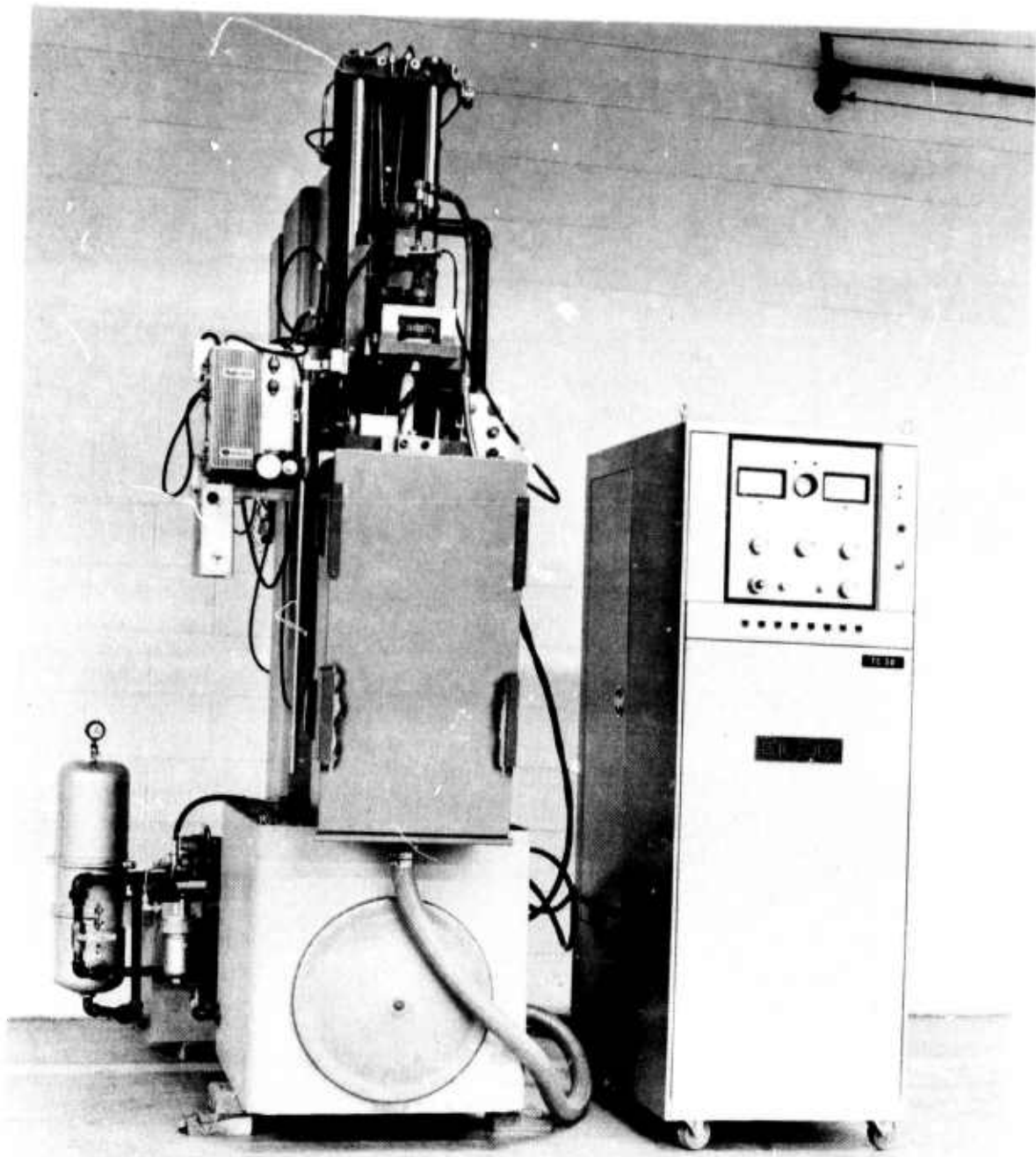


Figure 1. EDM Machining Center

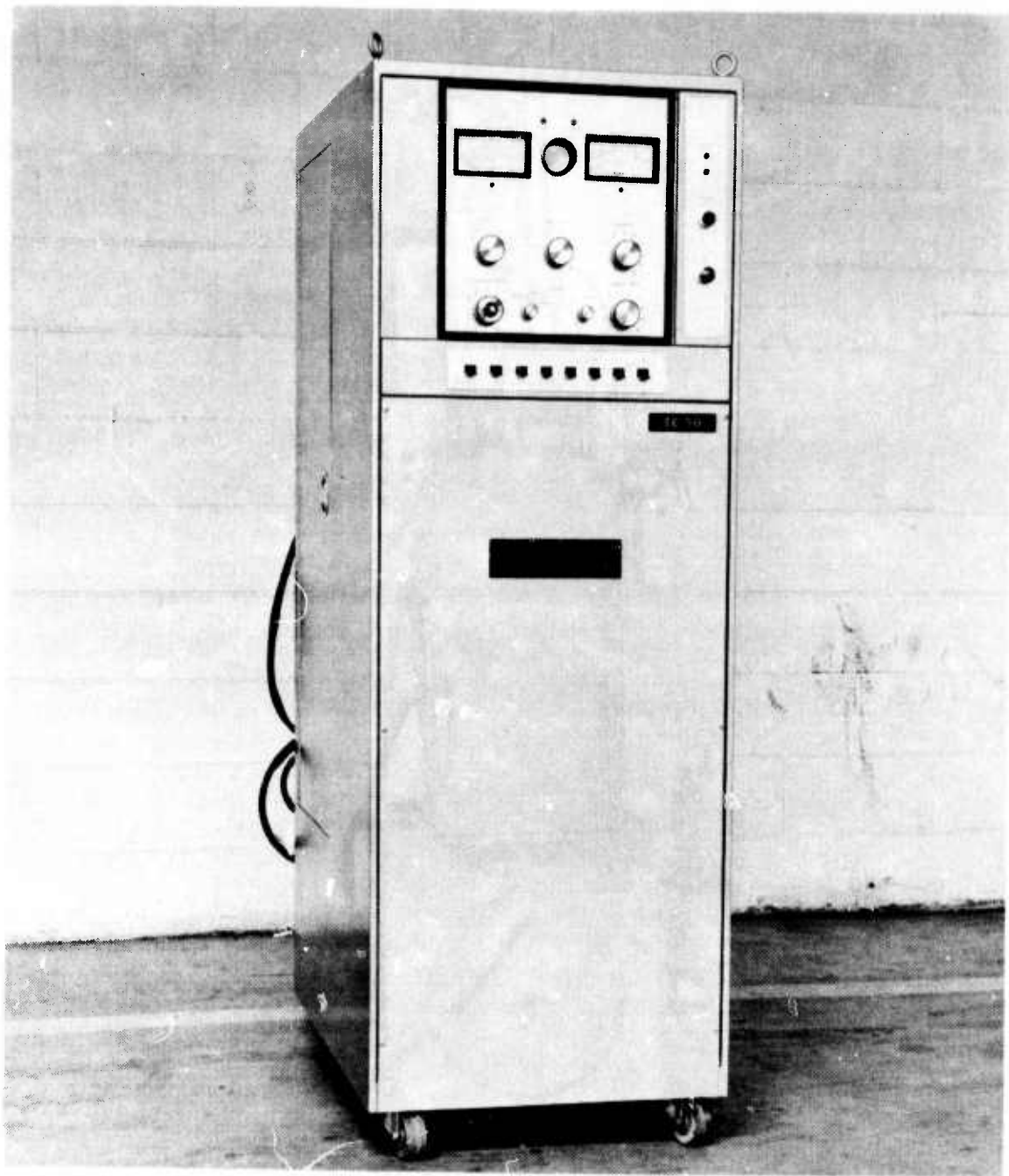


Figure 2. EDM Power Supply

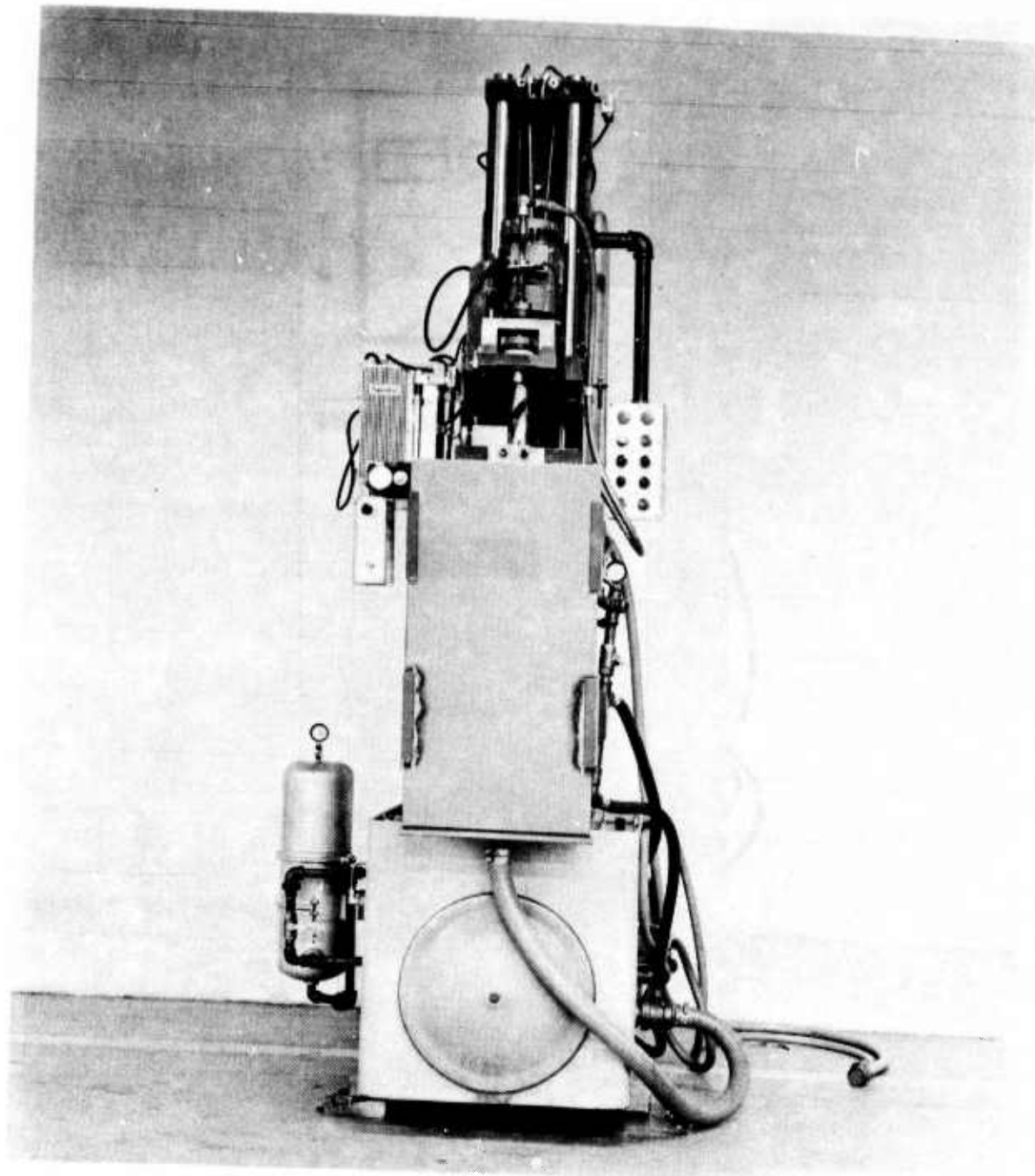


Figure 3. EDM Machine Tool

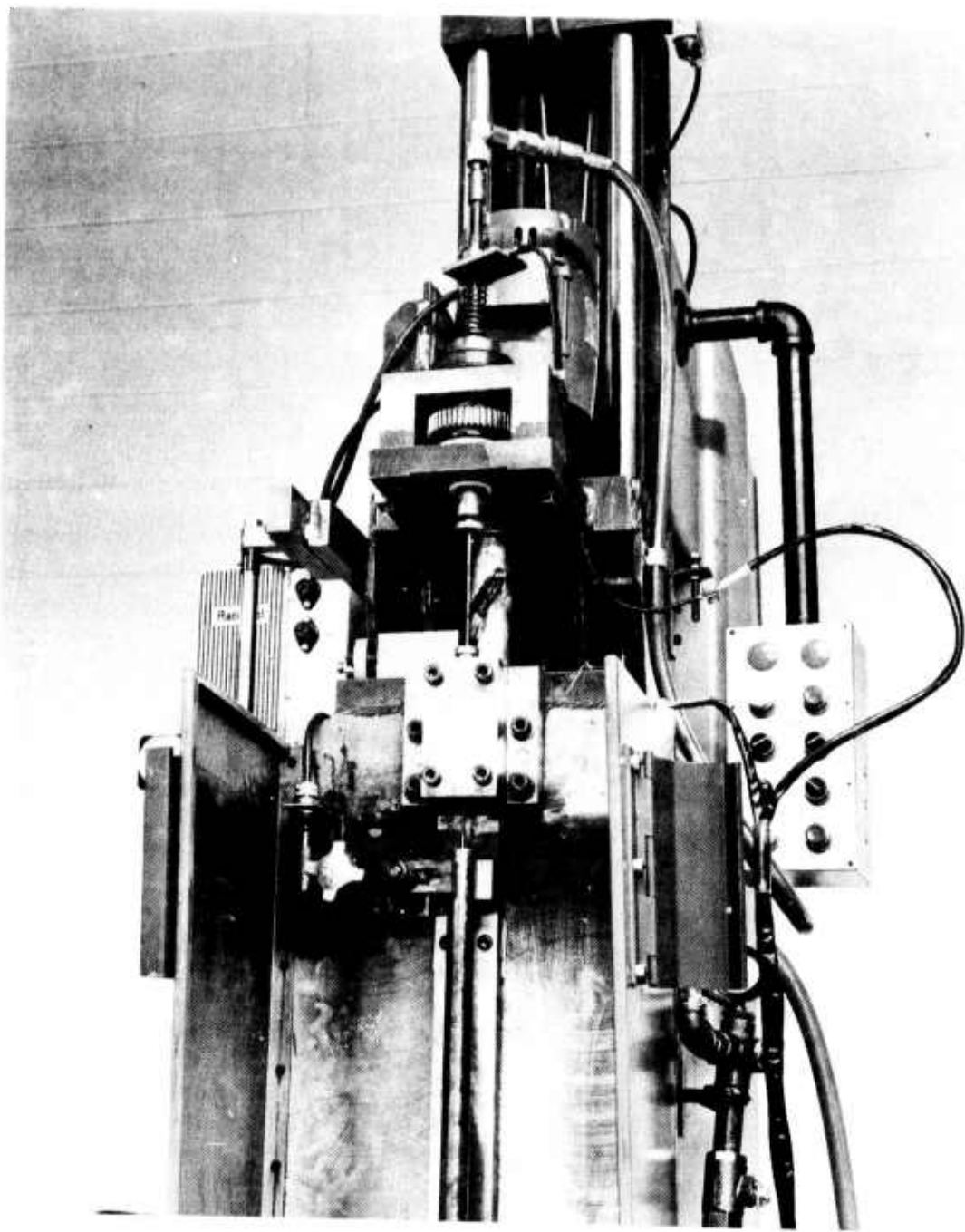


Figure 4. EDM Work Station

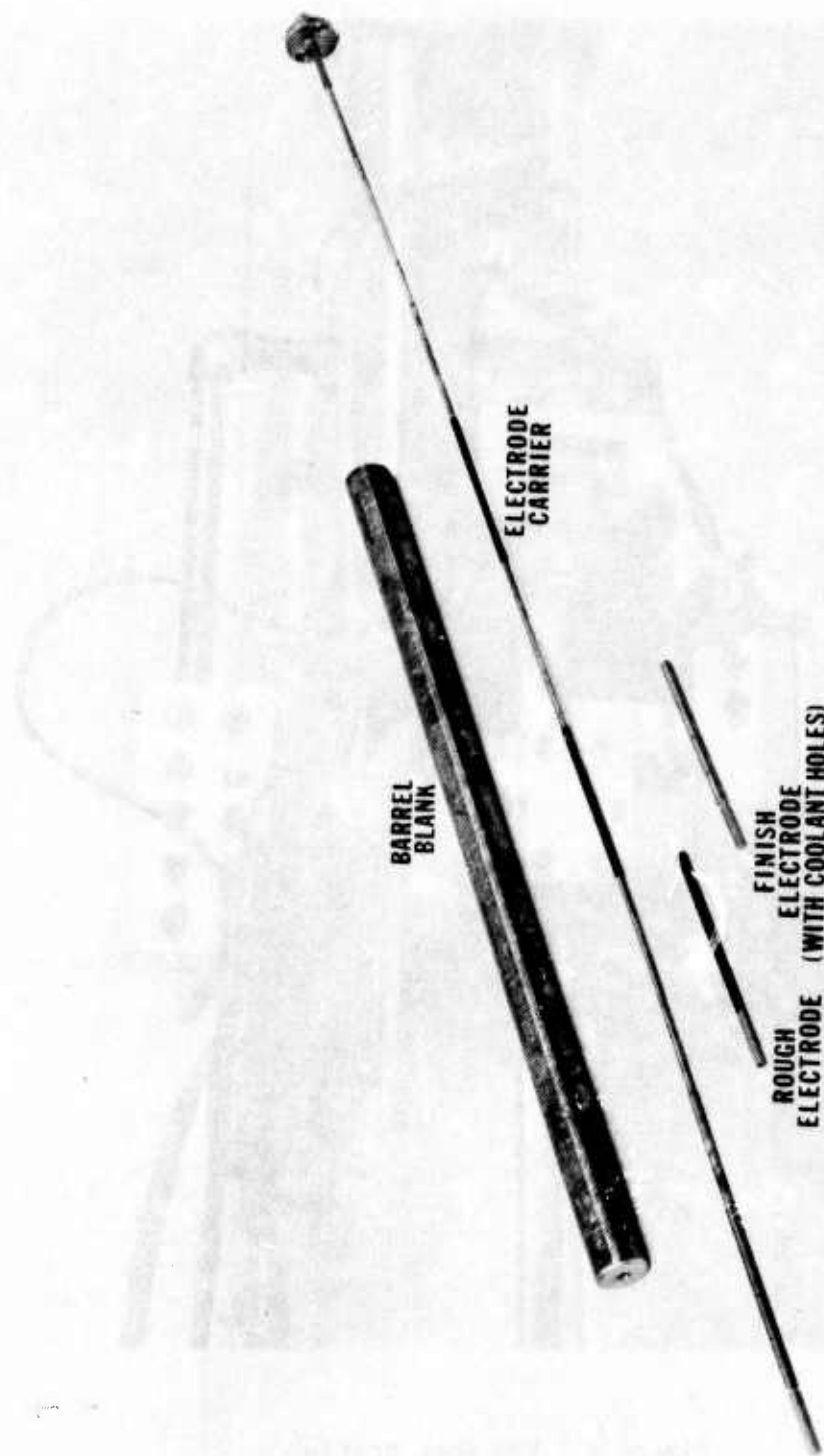


Figure 5. EDM Electrodes, Electrode Carrier

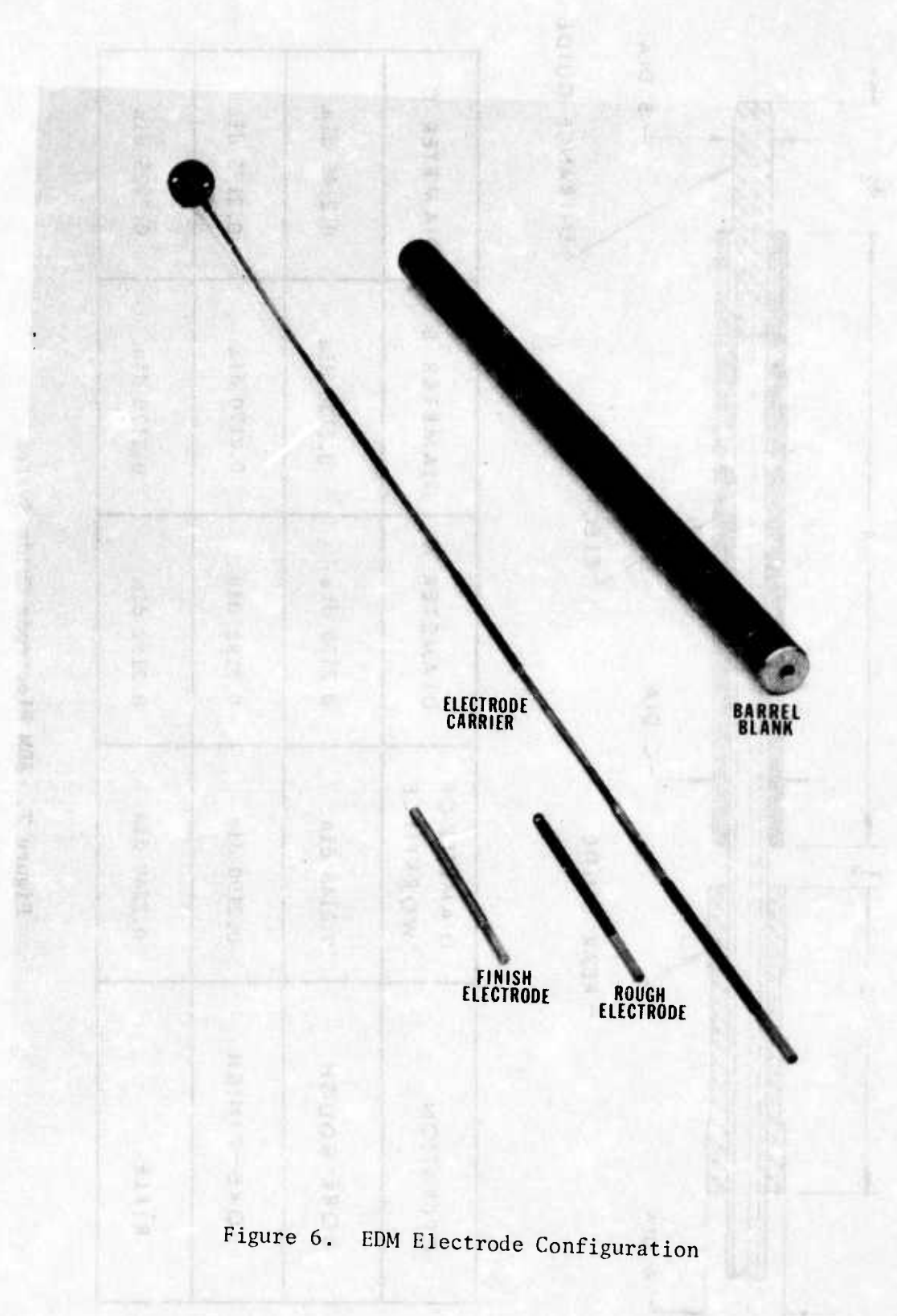
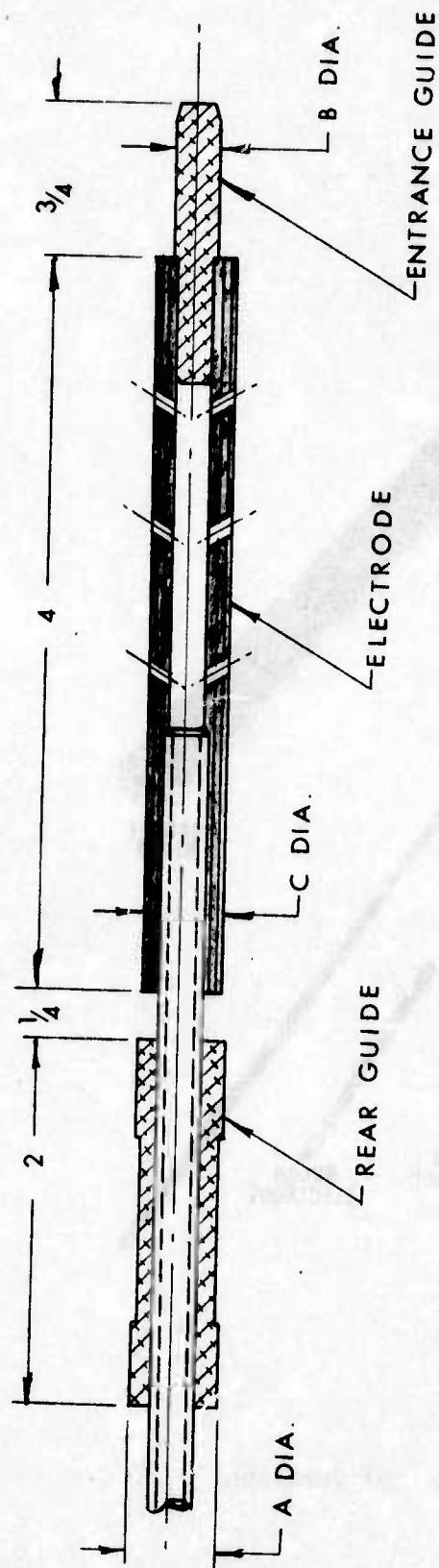
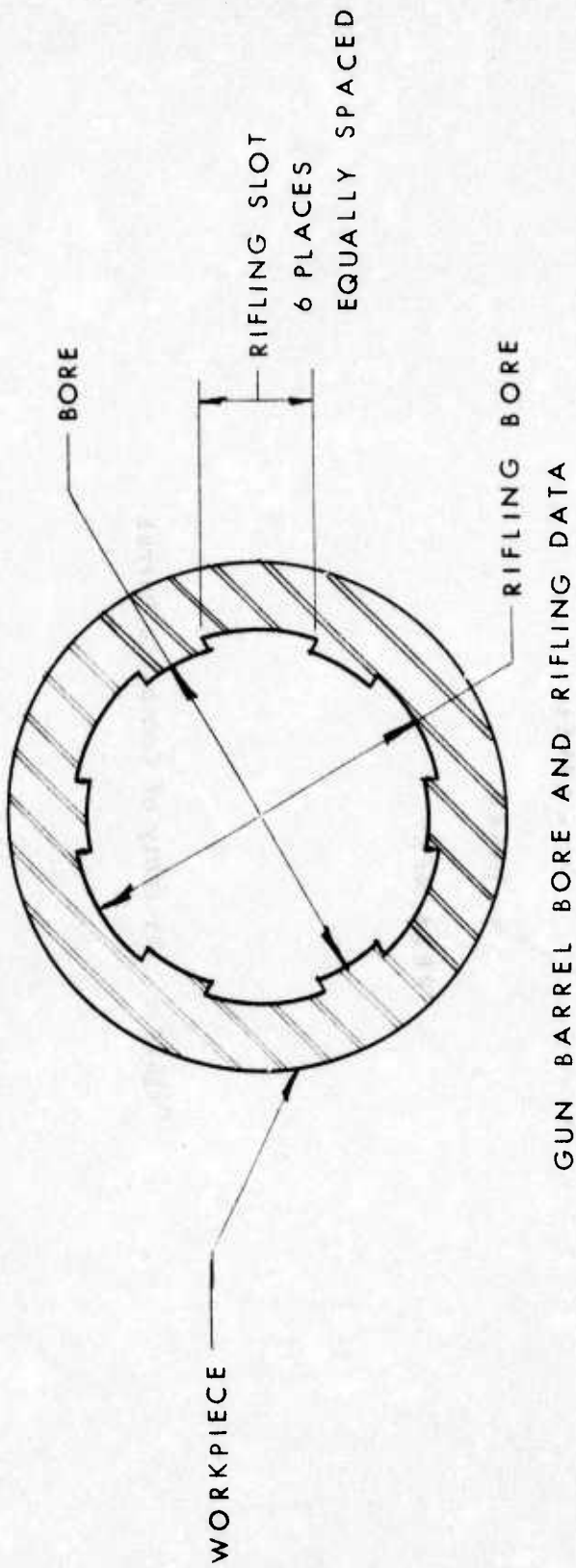


Figure 6. EDM Electrode Configuration



OPERATION	DIAMETER OF WORKPIECE	DIAMETER "A"	DIAMETER "B"	DIAMETER "C"
BORE-ROUGH	0.2145 dia.	0.2135 dia.	0.2120 dia.	0.2145 dia.
BORE-FINISH	0.2190 dia.	0.2182 dia.	0.2170 dia.	0.2175 dia.
RIFLE	0.2240 dia.	0.2182 dia.	0.2170 dia.	0.2225 dia.

Figure 7. EDM Electrode Guide System



OPERATION DESCRIPTION	CUTTING PARAMETERS			WORKPIECE SIZE	ELECTRODE SIZE
	FREQUENCY CYCLES/SEC	AMPERAGE	OVERCUT		
RIFLING - BORE	130,000	0.1 amp	0.001	0.2240 dia.	0.2225 dia.
RIFLING - SLOTS	130,000	0.1 amp	0.001	0.0750 dia.	0.0730 dia.
BORE - ROUGH	8,000	4 amp	0.001	0.2145 dia.	0.2125 dia.
BORE - FINISH	130,000	0.2 amp	0.001	0.2190 dia.	0.2175 dia.

Figure 8. EDM Electrode Size and Rifling Data

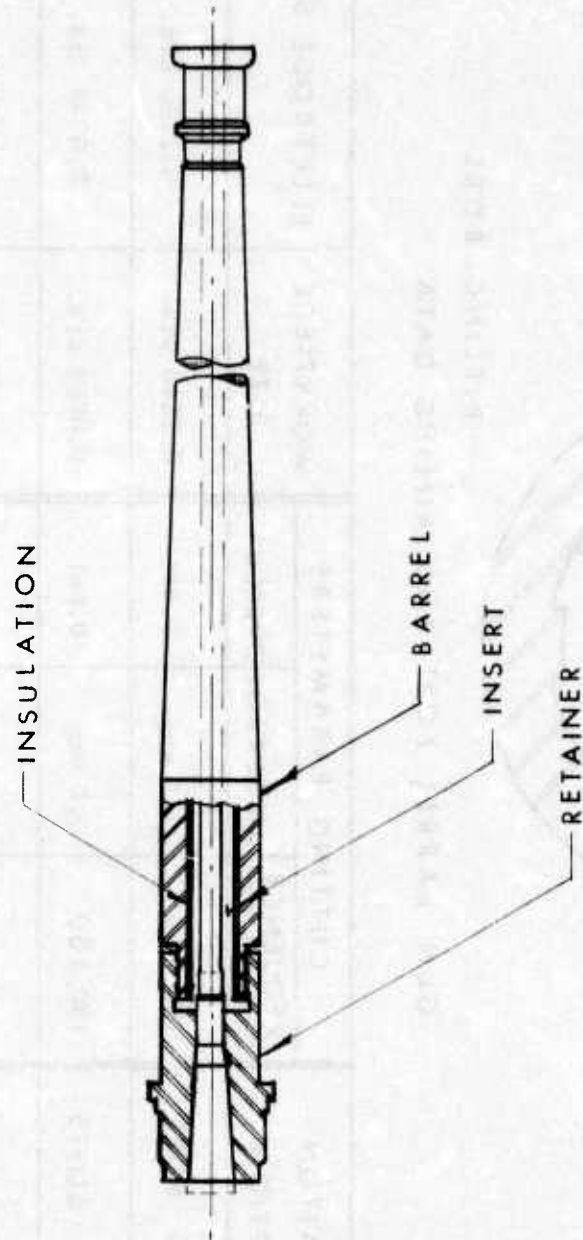
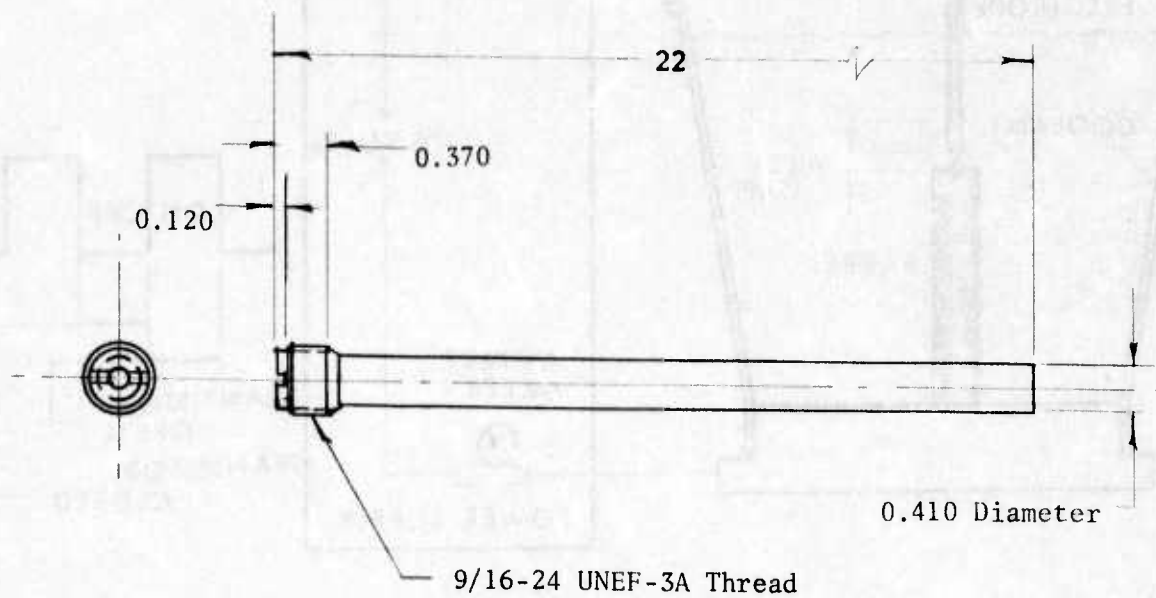


Figure 9. Assembly of Composite Barrel



BORE DIAMETER 0.2190 ± 0.001
 GROOVE DIAMETER 0.2240 ± 0.001
 NUMBER OF GROOVES 6
 GROOVE WIDTH 0.074 ± 0.002
 TWIST - R. H. SPIRAL . . . 1 TURN IN 10 INCHES

Figure 10. Composite Barrel Insert

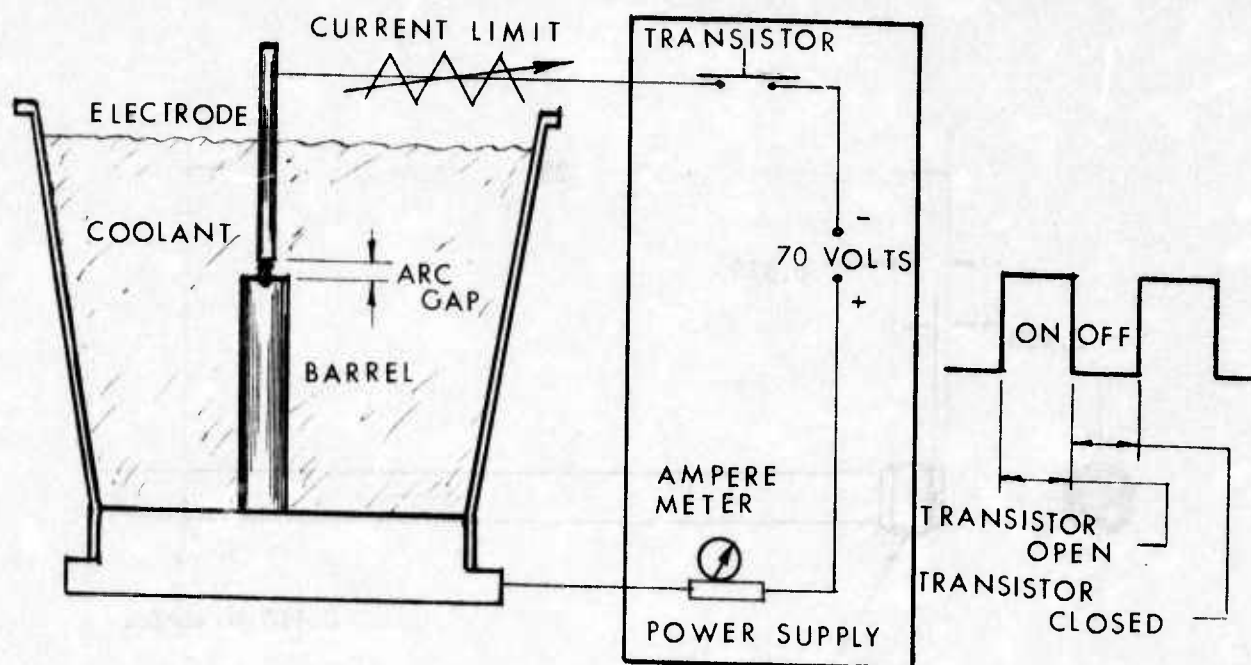


Figure 11. EDM Electrical Schematic

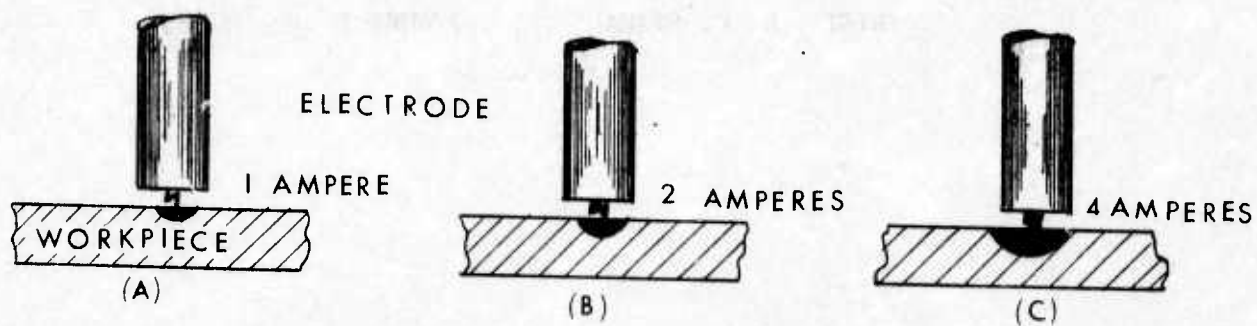
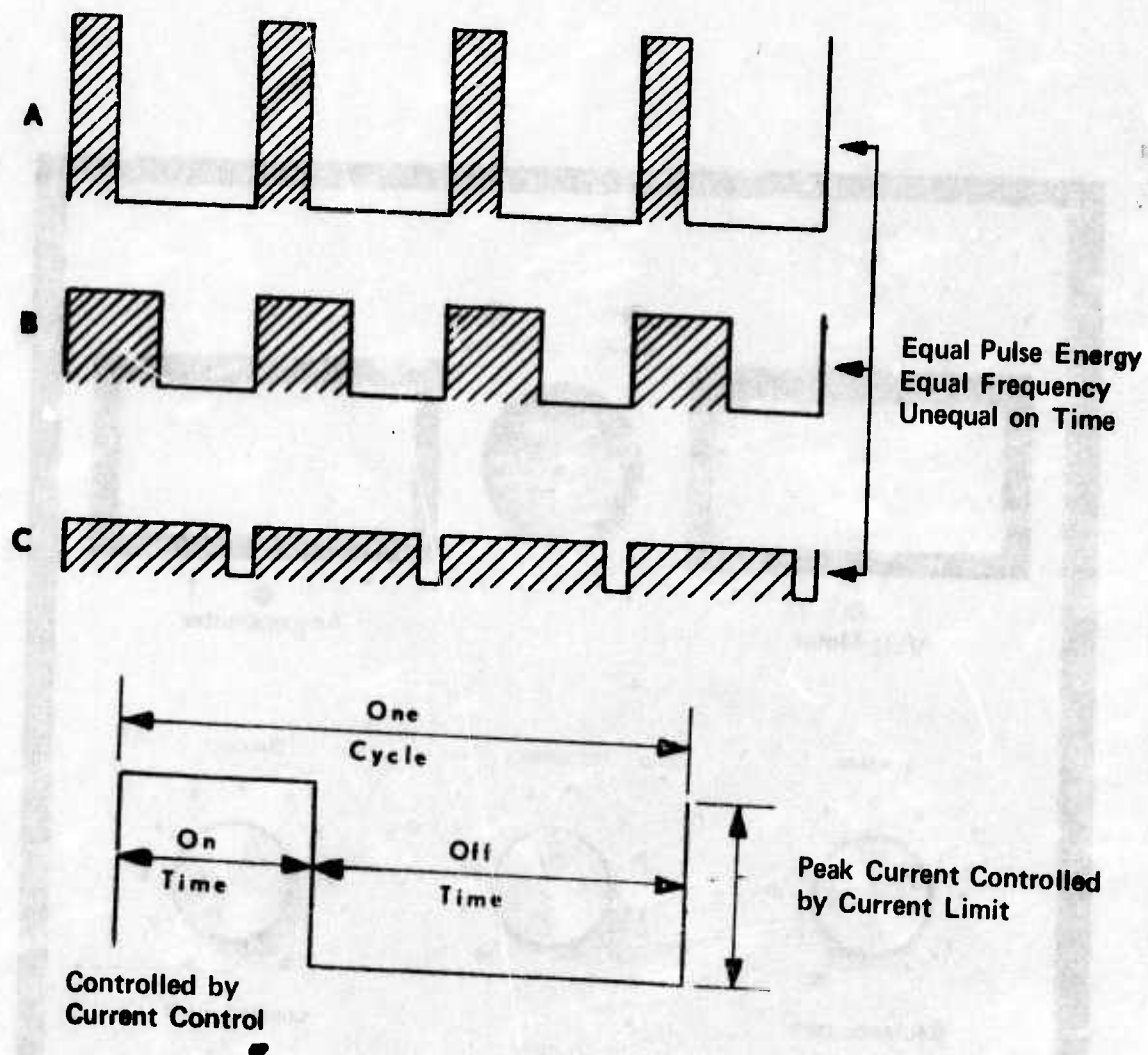
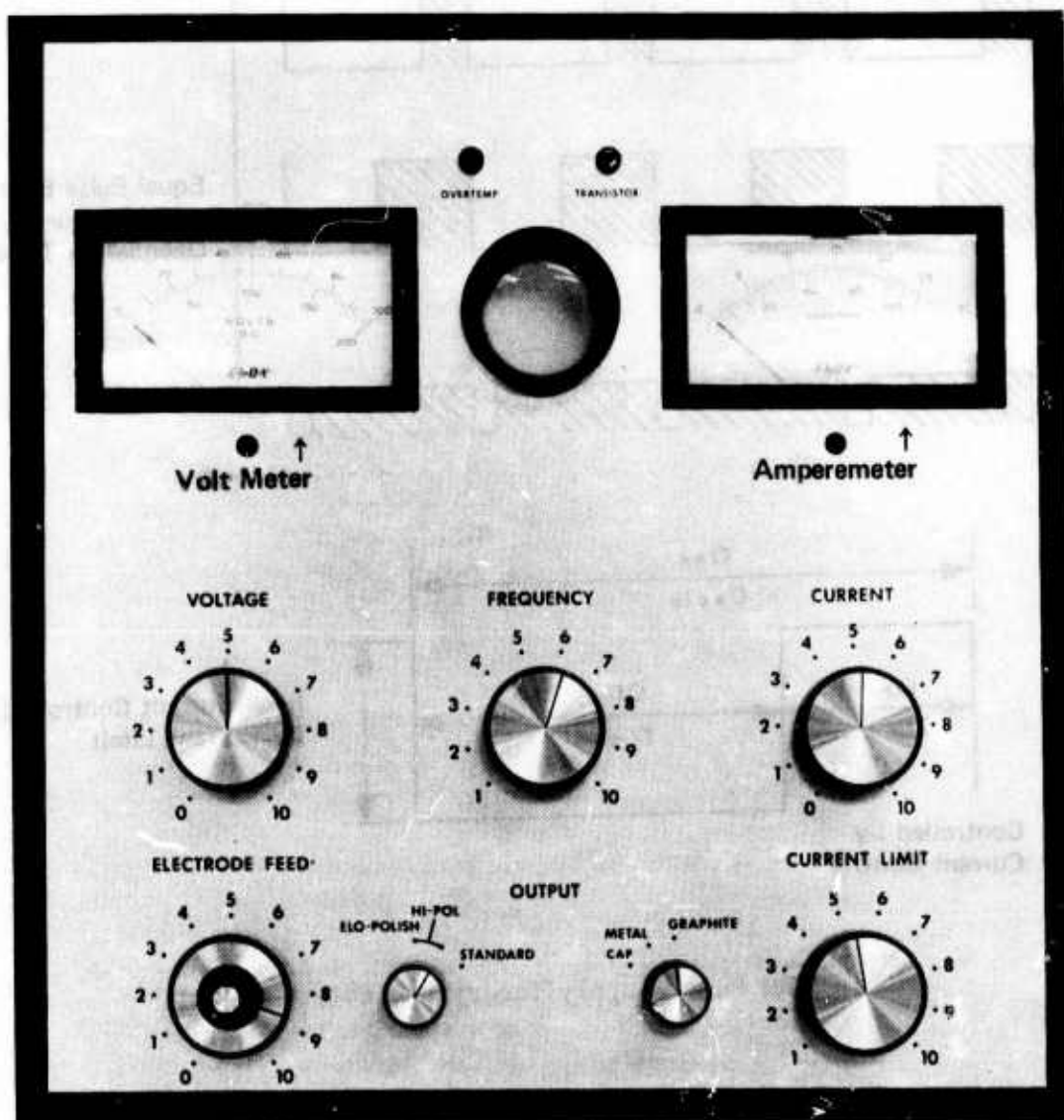


Figure 12. EDM Theory, Metal Removal Rate



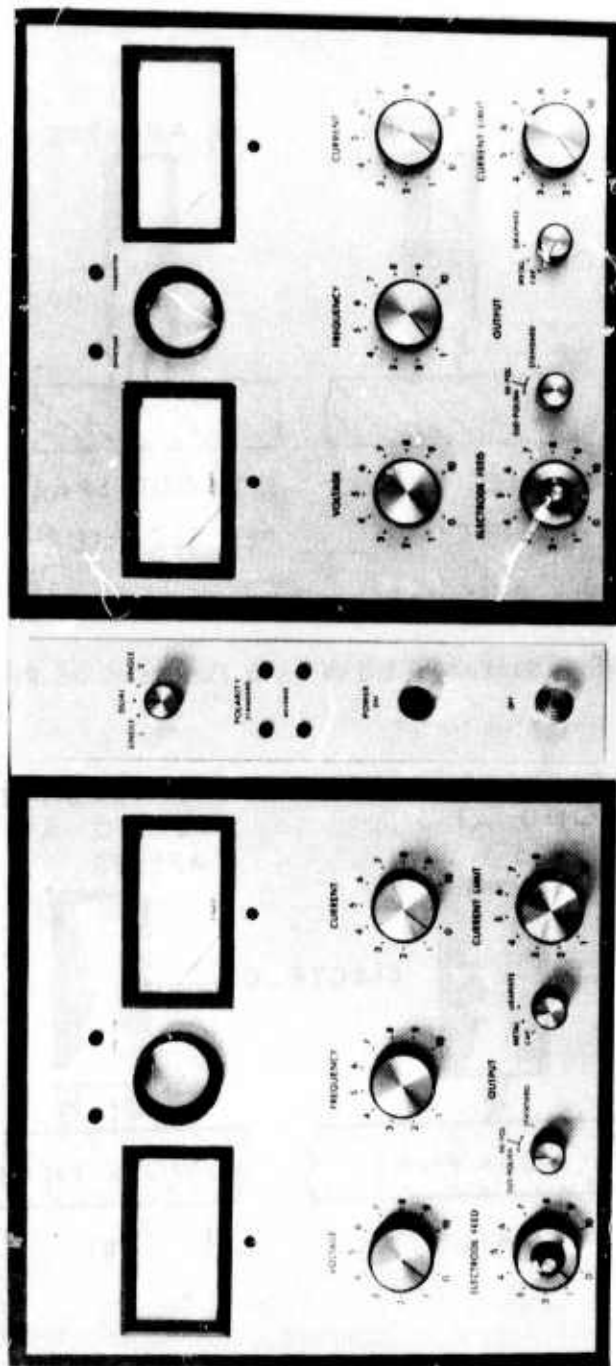
(a) EDM Power Supply Theory and Duty Cycle

Figure 13. EDM Power Supply Theory, Duty Cycle and Controls



(b) EDM Power Supply Control Explanation

Figure 13. EDM Power Supply Theory, Duty Cycle and Controls (Concluded)



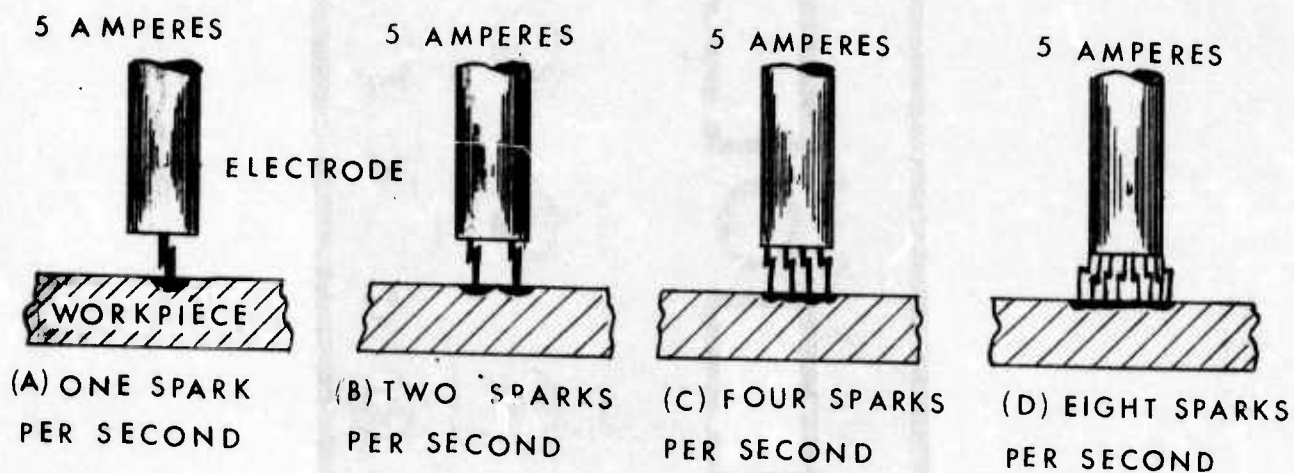


Figure 15. Surface Finish as a Function of Frequency

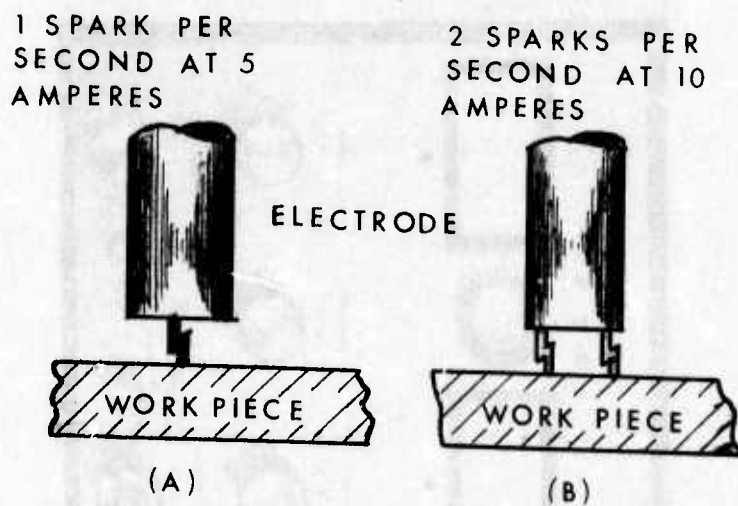


Figure 16. Surface Finish as a Function of Energy

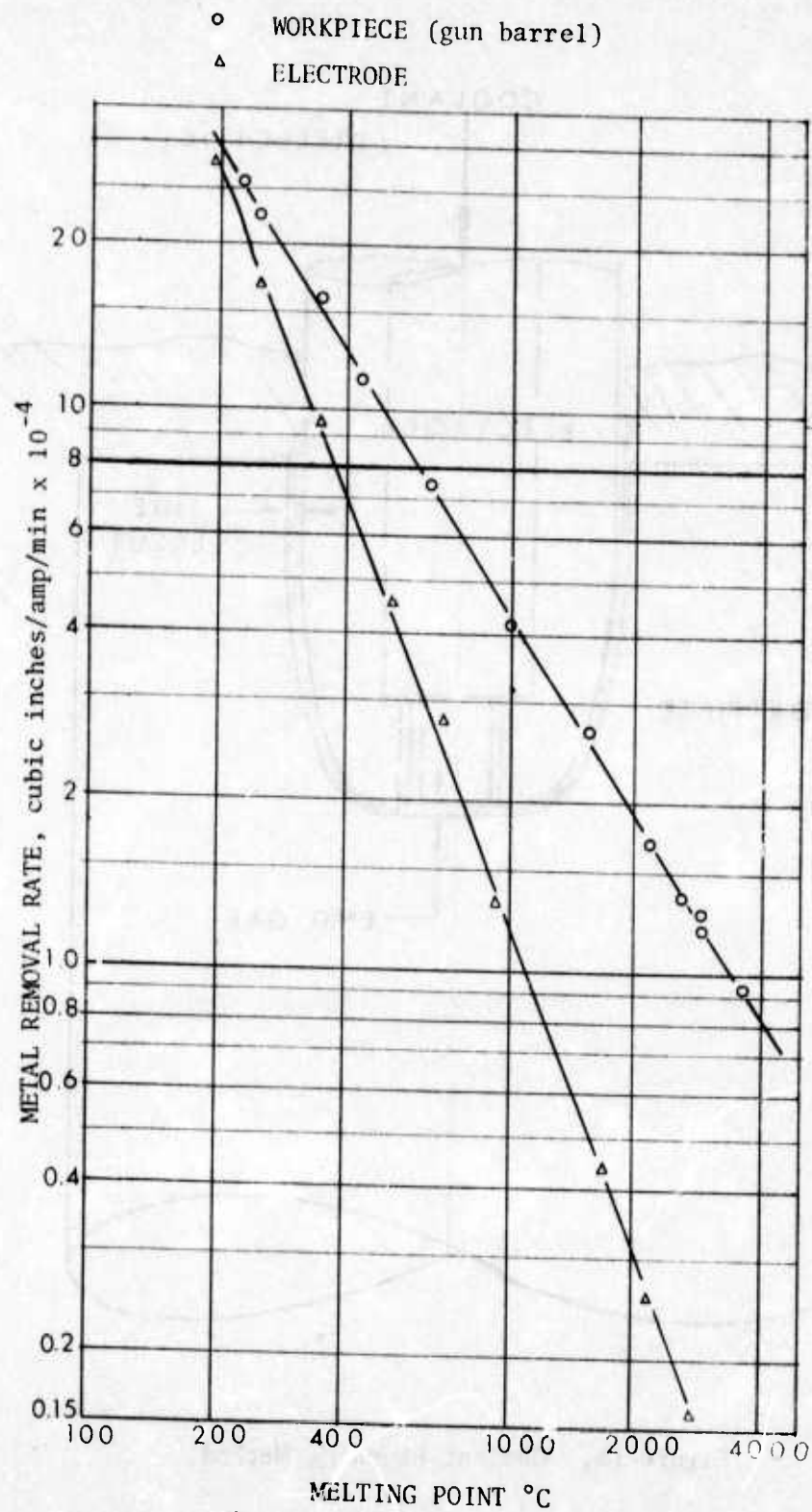


Figure 17. Average Metal Removal Rate Versus Melting Point

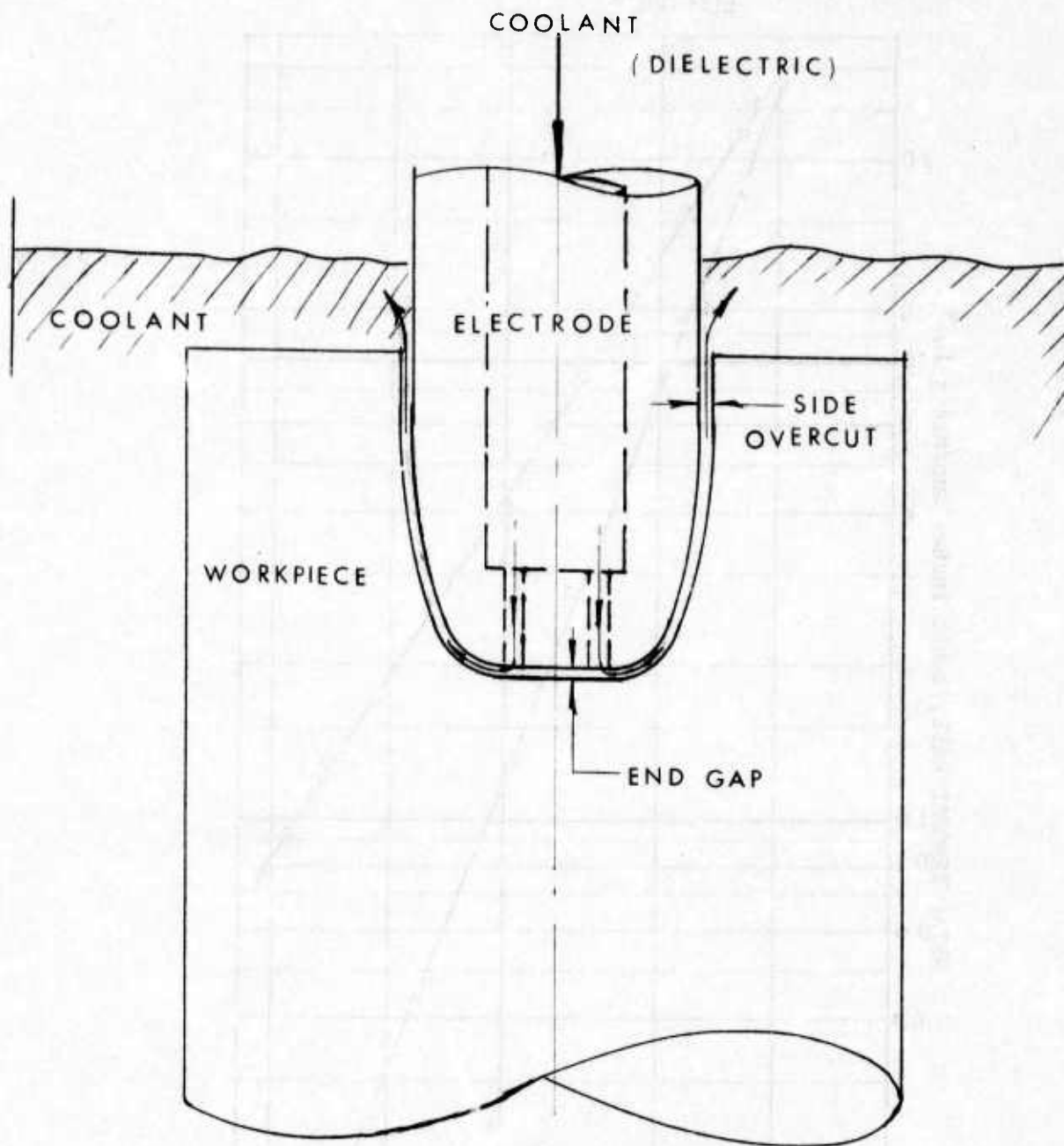
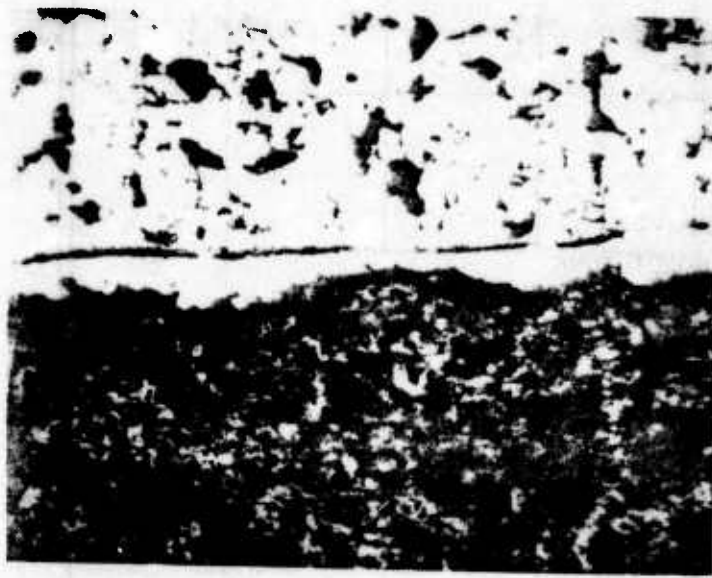


Figure 18. Coolant Flushing Method



Note: The surface of this sample shows a typical heat affected zone and the re-cast layers associated with EDM. The hardness of the recast layers could not be determined. A microhardness to R_C 32 was found at a depth of 0.001 inch beneath the surface.

Figure 19. Edge Photomicrograph of EDM Surface on CVD Tungsten Coated WC 3015 Material

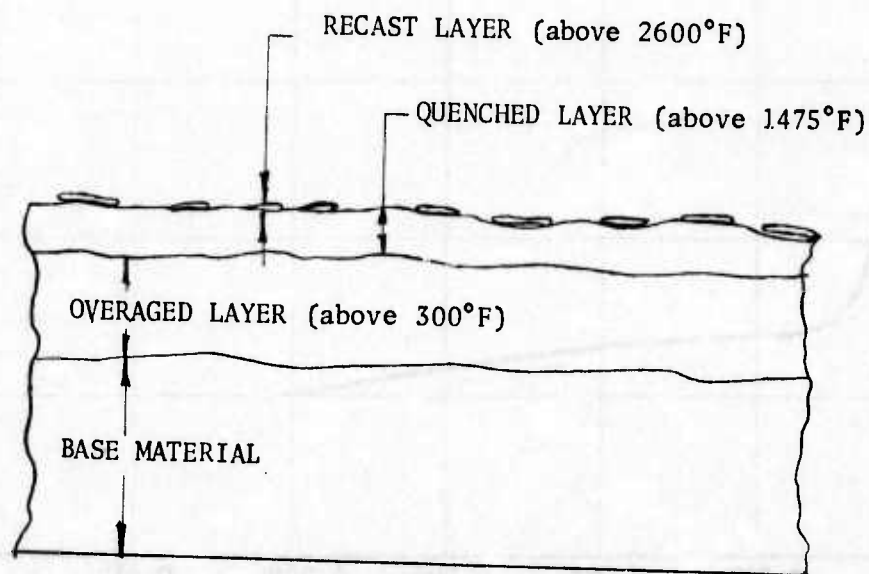


Figure 20. Layers of a Typical Edge Photomicrograph

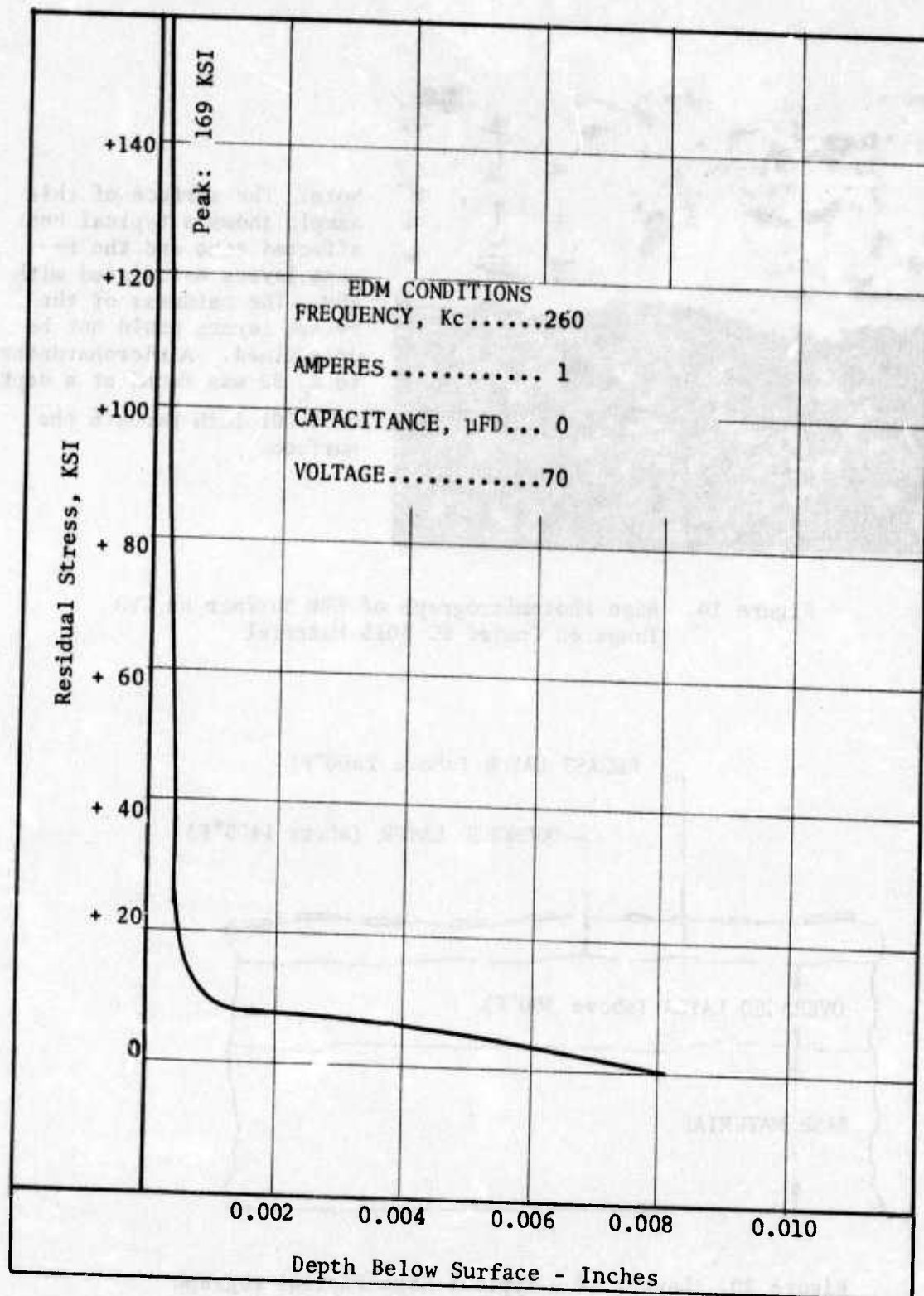


Figure 21. Residual Surface Stress Profiles in 17 -4 PH Steel Produced by EDM

TABLE 1. EDM TEST CUT PARAMETERS

MATERIAL	TEST NUMBER	FREQUENCY IN KILOHERTZ	ELECTRODE POLARITY	METAL REMOVAL RATE - CUBIC IN./AMP/MIN.	ELECTRODE WEAR	MATERIAL CONDITION
L-605	1	16	+	3×10^{-4}	100:1	C3
	2	16	-	5	7:1	C3
	3	16	-	3	6:1	C3
	4	32	+	2	100:1	3
	5	16	-	5	6:1	3
	6	32	-	7	6:1	3
	7	32	+	4	20:1	C1
	8	32	-	7	6:1	C1
	9	16	-	3	6:1	C1
	10	32	-	5	7:1	C1
	11	16	+	2	3:1	C3
	12	16	-	6	6:1	C3
	13	16	-	7	7:1	3
	14	16	+	1	50:1	3
	15	32	+	2	8:1	C1
L-605 CVD Tung. CVD Tung.	16	16	-	5	5:1	C1
	17	16	-	9	5:1	C3
	18	16	+	2	5:1	C3

TABLE 2. COMPARISON CHART: COPPER AND GRAPHITE VERSUS CANDIDATE MATERIALS

Some Physical Properties of Gun Barrel Blanks Selected for EDM Evaluation		
Material	Melting Point, Degrees Fahrenheit	Tensile Strength at Room Temperature - KPSI
TA-10W	5495	160
VM 103	2600	34
L-605	2425	23
INCO 718	2200	70
CG 27	2300	85
CVD Tung. Coated	6170	260
Graphite	6740	8-10
Copper	1981	32

TABLE 3. SUMMARY OF EDM CUTTING TIMES

BARREL MATERIAL	QUANTITY	AVERAGE TIME PER PART: HOURS			NUMBER OF ELECTRODES		
		ROUGH BORE	FINISH BORE	RIFLE	ROUGH	FINISH	RIFLE
VM 103	4	30	*	--	4	3	--
CG 27	8	2.5	1.5	2.5	1	1	1
L-605	4	3.5	2	2.0	1	1	1
INCO 718	5	2.6	2	3.0	1	1	1
TA-10W	1	38	*	*	3	3	--
CVD TUNG. COAT	1	46	*	*	6	4	--

* Test Cut Terminated.

TABLE 4. QUALITATIVE COMPARISON OF MACHINABILITY RATINGS OF CANDIDATE MATERIALS

MATERIAL TYPE	GUN DRILLING AND HONING	RIFLING	TURNING	EDM RATING	OVERALL RATING
CG 27	B	B	B	A	B
L-605	C	B	B	A	B+
VM 103	C	B	C	D	D
TA-10W	D	E	D	D	D-
INCO 718	B	B	B	A	B+
CVD TUNG. COAT (10 mil)	D	E	D	E	E+

* EXPLANATION OF COMPARITIVE MACHINABILITY RATING				
	DIFFICULTY ENCOUNTERED	MACHINING TIME REQUIRED	SURFACE FINISH ACHIEVED	
A (Excellent)	None	Low	Good	
B (Good)	Low	Medium	Good	
C (Fair)	Medium	Medium	Good	
D (Poor)	High	High	Good	
E (Very Poor)	High	High	Poor	

TABLE 5. BARREL BORE PROCESSING SUMMARY

Barrel Material	Barrel Bore Manufacturing Method							
	FDM Bore From Blank		Gun Drill Initial Bore undersize		Bore Completed By FDM		Not Completed	
	Serial Number	Qty.	Serial Number	Qty.	Serial Number	Qty.	Serial Number	Qty.
CG 27	—	0	1, 1a, 2, 2a, 3, 3a	6	1, 1a, 2, 2a, 3, 3a	8	—	0
INCO 718	4	1	4a, 5, 5a, 6, 6a	5	4a, 5, 5a, 6, 6a	5	—	0
L-605	7a, 9	2	7, 8, 8a, 9a	4	7, 8, 8a, 9a	4	—	0
VM 103	—	0	7, 8, 8a, 9a	4	7, 8, 8a, 9a	4	7a, 11, 11a	3
TA-10W	13, 13a, 14a	3	14, 15a, 15	3	—	0	13, 13a, 14, 14a, 15, 15a	6
CVD Tung.	NA	0	NA	0	NA	0	NA	6
Total Barrels		6		18		21		15

INITIAL DISTRIBUTION

USAF/RDQRM	2	AFIS/INTA	1
USAF/SAMI	1	Elox Div, Colt Ind	3
ASD/ENYS	1		
TAC/DRA	1		
SAC/LGWC	1		
SAC (NRI/STINFO Lib)	1		
CIA (CRE/ADD/Publications	2		
AFWL/LR	1		
AUL/AUL-LSE-70-239	1		
Ballistic Res Labs (AMXBR-TB)	1		
Naval Sys Cntr (Tech Lib, 154)	1		
Commander, NWC (Code 4565)	1		
ONR (Code 473)	1		
NASA STINFO Fac	1		
Univ of Calif, Lawrence Rad Lab, Chem Dept/L-402	1		
Univ of Calif, Lawrence Rad Lab, Tech Info Dept/L-3	1		
Los Alamos Science Lab (Report Lib)	1		
Chem Prop Info Agency (Applied Physics Laboratory	2		
Battelle Memorial Inst (Report Lib)	1		
Sandia Lab (W. H. Curry Div 5625)	2		
The Rand Corp (Lib-D)	1		
Harry Diamond Labs (AMXDP-TC)	1		
DDC/TC	2		
USAFTFWC/TA	1		
Commander, Naval Weapons Lab	1		
Watervliet Arsenal (SARWV-RDT-L)	1		
Plastec-Bldg 176, Picatinny Arsenal	1		
A-E-R-O, Dr Nicolaidis	1		
Alpha Research Inc	1		
Ogden ALC/MMNOP	2		
Picatinny Arsenal (SARPA-FR-S-A)	1		
US Atomic Energy Commission (Hqs Lib)	1		
AEDC/ARO, Inc	1		
USA Material Command (AMCRO-WN)	1		
Office of the Chief of Nav Opns Air Warfare Br (OP-982E)	1		
PACAF/LGWLE	4		
TAWC/TRADOCLO	1		
AFATL/DL	1		
AFATL/DLOSL	2		
AFATL/DLDG	10		
ADTC/WE	1		
ASD/ENYEHM	1		

**READ INSTRUCTIONS
BEFORE COMPLETING FORM**

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Item 20 (Concluded):

and GAU-8/A. The materials investigated were iron/nickel base superalloys, cobalt base superalloys, tantalum, columbium, and tungsten refractory alloys. These materials do not lend themselves to nontraditional types of machining, and an investigation was undertaken to see if advances in the state of the machining art, such as EDM, were capable of the task. The final effort on the program consisted of boring and rifling 18 gun barrel blanks for delivery to Philco-Ford Corporation, Aeronutronic Division, Newport Beach, California, for final fabrication and testing in .220 swift M-60 test barrels. These barrel blanks, however, were out of specification and could not be fabricated into test barrels.

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